Building and Environment 49 (2012) 348–358

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Remotely sensing the cooling effects of city scale efforts to reduce urban heat island

Christopher W. Mackey [a,*], Xuhui Lee [b], Ronald B. Smith [c]

[a] Center for Earth Observation, Yale University, 21 Sachem Street, New Haven, CT 06511, USA
[b] School of Forestry & Environmental Studies, Yale University, 195 Prospect Street, New Haven, CT 06511, USA
[c] Department of Geology and Geophysics, Yale University, P.O. Box 208109, New Haven, CT 06520-8109, USA

ARTICLE INFO

Article history:
Received 6 June 2011
Received in revised form
27 July 2011
Accepted 6 August 2011

Keywords:
Urban heat island
Chicago
Albedo
NDVI
Vegetation
Reflective roof

ABSTRACT

While recent years have seen many analyses of techniques to reduce urban heat island, nearly all of these studies have either been evaluations of real small scale applications or attempts to model the effects of large scale applications. This study is an attempt to analyze a real large scale application by observing recent vegetated and reflective surfaces in LANDSAT images of Chicago, a city which has deployed a variety of heat island combative methods over the last 15 years. Results show that Chicago's new reflective surfaces since 1995 produced a noticeable impact on the citywide albedo, raising it by about 0.016, while citywide NDVI increase is around 0.007. This finding along with counts of pixels with increased albedo and NDVI suggest that the reflective strategies influenced a larger area of the city than the vegetative methods. Additionally, plots between albedo increase and corresponding LANDSAT temperature change over the test period have linear regressions with steeper slopes (−15.7) and stronger linear correlations (−0.33) than plots between NDVI increase and temperature change (−8.9 slope, −0.17 correlation). This indicates that the albedo increases produced greater LANDSAT cooling than the NDVI increases. Observation of aerial images confirmed that typical instances of efforts to increase albedo, such as reflective roofs, produced stronger LANDSAT cooling than common instances of NDVI efforts, such as green roofs, street trees and green spaces. Accordingly, the reflective strategies were likely much more effective at cooling Chicago's LANDSAT heat island and may signify a generally more effective strategy for similar cities.

1. Introduction

Since the first observations of the urban heat island (UHI) effect, in which urban areas can be a few degrees warmer than surrounding rural areas, there has been a growing agreement that strategies to cool cities must be developed and tested. The present urbanization projections that estimate 6.3 billion people living in cities by 2050 have intensified the need to make urban environments more comfortable and livable [27]. At the same time, recent concerns about energy consumption have placed emphasis on minimizing the energy used to achieve thermal comfort, urging people to rely on passive ventilation from their UHI-altered surroundings [22]. Moreover, with global warming projections threatening to further increase urban temperatures world-wide, urban cooling techniques may prove even more important in the coming decades [22].

Faced with these issues, many scientists are developing a number of possible urban cooling strategies [14,28] and two have gained acceptance to the point that they are being implemented in a number of cities. These implemented strategies include one that seeks to increase urban reflectivity [6] and another that seeks to increase urban vegetation [10]. Both of these accepted methods focus on mitigating one of the primary causes of UHI outlined by [18] – the fact that urban materials, when compared to rural materials, tend to have properties conducive to higher temperatures. These properties include lower moisture contents, lower thermal roughness lengths, and lower surface albedos. By increasing the reflectiveness of urban surfaces, the former strategy helps remove solar radiation that would otherwise be converted into heat. In the latter strategy, increased vegetation provides enhanced evapotranspiration, which converts absorbed solar radiation into latent heat instead of sensible heat [12]. Additionally, increasing vegetation increases land surface roughness, which

* Corresponding author. Present address: 24 Denton Court, Rockville Centre, NY 11570, USA. Tel.: +1 516 509 0165.
E-mail addresses: christopher.mackey@yale.edu, chris@mackeyarchitecture.com (C.W. Mackey), xuhui.lee@yale.edu (X. Lee), ronald.smith@yale.edu (R.B. Smith).

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doi:10.1016/j.buildenv.2011.08.004

promotes the transfer of heat to the air and the convection of heat away from the ground [4]. Typical urban strategies belonging to the former category include the installation of reflective roofs or pavement [23] while strategies belonging to the latter category include the introduction of vegetation by means of green roofs, street/yard trees, and green spaces [10].

Numerous studies have revealed that both the reflective and vegetative strategies have the potential to significantly cool urban environments. However, these studies have either been on a small scale, observing individual instances of cooling method application [7,8,23,25]; or they have been attempts to model what would happen if such methods were adopted on a city scale or larger [1,2,6,24]. This study is one of the first to present data regarding the actual implementation of urban cooling strategies on a city scale. Up until this point, the cooling efforts of most cities appear to be too small to have noticeable impacts on this scale and their effects are likely indistinguishable amid other alterations such as land use change with development. However, after almost two decades of minimal development while implementing UHI-combative strategies in both the vegetated and reflective categories (outlined in Appendix A), the city of Chicago has established itself as an optimal testing ground for the comparison of such efforts.

This study's analysis of Chicago's cooling efforts is particularly helpful for informing the debate over the comparative effectiveness of the reflective and vegetated methods. To date, this debate has been informed only by the aforementioned means of analysis and this has had limitations in terms of the complex issues cities face as they seek to reduce their temperature. For example, while the replacement of vegetation with impermeable surfaces is a major cause of UHI and one should probably favor vegetated surfaces over impermeable ones when drafting cooling strategies [16]; some studies have revealed that this may not always be the best route to follow. One multi-year study in Hyōgo, Japan found that highly reflective impermeable white roofs were slightly cooler than grassy green ones, suggesting that these roofs could compete with vegetative methods [25]. Supporting these findings are a number of studies verifying that vegetation must be dense and include shrubs/trees in order to produce the large cooling effects needed to affect changes on a city scale [5,8,19]. When viewed in relation to vegetation-based strategies, this may arouse economic concerns since dense vegetation often has high planting and maintenance costs in urban areas. Some have suggested that the additional ecosystem services offered by a vegetative strategy, such minimized storm water runoff and air purification, might be enough to make it a worthwhile investment [17,20]. However, it is difficult to quantify the value of such benefits and understand how they will impact the effectiveness of strategies as they are implemented over an entire city.

It is because of complications such as these that information on the actual implementation of cooling strategies over cities is particularly helpful. Issues such as maintenance costs and ecological services are difficult to factor into computer models and observations of small-scale applications often have unique situations that are different than that of an entire city. Accordingly, this study will observe a real-world example in an attempt to address some of the limitations in these previous studies. Specifically, this study will observe the citywide increases in Chicago's vegetation and albedo over the last 15 years and compare each of their effects on remotely-sensed surface temperature.

2. Material and methods

Data collection began with the selection of LANDSAT 5 images to represent Chicago at present and prior to the implementation of cooling strategies (around 1995). Only the area within the political borders of the city was considered for analysis since it was within these limits that the most intense and organized efforts took place. An attempt was made to find images without cloud cover, with comparable anniversary dates, and with similar atmospheric conditions in order to minimize error in the comparison of the images' vegetation, albedo and surface temperatures. Ultimately, 8 individual images were selected and these were arranged to produce 5 pairs of past/present images. Table 1 displays data regarding the atmospheric conditions of the images and illustrates that the disparities between each of the pairs are not great enough to compromise the integrity of the analysis. In the course of the study, the only disparity that seems to have produced an anomalous result was the difference in previous day's and month's precipitation in Image pair 5. However, the pair represents an interesting finding that may have relevance for long-term cooling strategies factoring in precipitation increases from global warming and, thus, it was kept in the study. It is important to note that,

Table 1
The atmospheric conditions over Chicago when each of this study's LANDSAT images was taken. "Ground" refers to values that are an average between those recorded at O'Hare International Airport and Midway Airport in the hour the satellite passed overhead. "Balloon" refers to an average of values recorded at a pressure/height of 925 hpa by weather balloon soundings in nearby Lincoln, IL and Davenport, IL. Since soundings occur every 12 h, the values were interpolated to the time that the satellite passed over.

Date	Average LANDSAT surface temp. (°C)	Ground air temp (°C)	Ground Dewpt. (°C)	Balloon air temp (°C)	Balloon Dewpt. (°C)	Ground wind speed (km h-1)	Prev. day's rain (cm)	Prev. month's rain (cm)	Percent of city in cloud/shadow
Image Pair 1									
May 30 1995	29.8	22.9	13.1	15.1	4.5	6	0.0	8.9	0.0
June 5 2009	30.9	20.6	6.4	14.7	3.0	14	0.0	14.2	0.0
Difference	**+1.1**	**−2.3**	**−6.7**	**−0.4**	**−1.5**	**+8**	**0.0**	**+5.3**	**0.0**
Image Pair 2									
July 3 1996	31.3	22.9	14.0	16.5	10.5	21	0.0	11.4	1.5
July 2 2007	30.2	21.5	8.8	17.9	6.8	15	0.4	6.4	0.0
Difference	**−1.1**	**−1.4**	**−5.2**	**+1.4**	**−3.7**	**−7**	**+0.4**	**−5.0**	**−1.5**
Image Pair 3									
June 15 1995	32.4	27.5	13.8	18.1	9.9	10	0.3	8.1	0.0
June 16 2007	35.0	30.5	15.3	24.0	11.1	14	0.0	5.5	0.0
Difference	**+2.6**	**+3.0**	**+1.5**	**+5.9**	**+1.2**	**+4**	**−0.3**	**−2.6**	**0.0**
Image Pair 4									
July 1 1995	29.8	20.3	8.2	12.3	5.5	17	0.0	6.6	2.4
July 2 2007	30.2	21.5	8.8	17.9	6.8	15	0.4	6.4	0.0
Difference	**+0.4**	**+1.2**	**+0.6**	**+5.6**	**+1.3**	**−3**	**+0.4**	**−0.2**	**−2.4**
Image Pair 5									
June 15 1995	32.4	27.5	13.8	18.1	9.9	10	0.3	8.1	0.0
June 24 2010	32.0	23.7	15.9	18.4	12.2	16	3.1	18.6	4.0
Difference	**−0.4**	**−3.8**	**+2.1**	**+0.3**	**+2.3**	**+6**	**+2.8**	**+10.5**	**+4.0**

because all the images of the study are from LANDSAT 5, all images of Chicago were taken at the same time of day (10:29 AM) and have comparable sun angles for images with similar anniversary dates.

After the LANDSAT images were selected, their digital numbers were converted to radiance or reflectance using information in the header files and a series of algorithms in the software ENVI. Next, pixels outside the Chicago political border were masked using a vector file obtained from the city government. Additionally, the three images that possessed cloud cover in their scenes (see Table 1) had their cloud and cloud shadow pixels manually masked.

In order to further minimize the errors caused by differences in atmospheric conditions, an atmospheric correction was performed on all five pairs. This began with the designation of 29 pixels throughout the city that represent objects of very stable reflectance. While 29 pixels is a small number of pixels in relation to the size of Chicago, observation of aerial images revealed great uncertainty with the stability of many surfaces in the city over the 15-year period. For example, streets and playing courts were often repaved or became weathered, light roofs accumulated dust, bare soil and vegetated surfaces changed in vegetation content, and shallow water bodies changed in algae levels. Most pixels in Chicago included a portion of these land cover types and were subsequently unsuitable for this correction strategy. Accordingly, only the few surfaces that were identified in aerial imagery as having undergone the smallest change were used. These mostly included deep water bodies, large dark warehouse roofs, and sections of concrete pavement at airports. A linear regression of the individual band reflectance values of the selected 29 pixels was derived between the past and present images of each pair. The equation of this regression was then applied to one of the images in each pair in order to correct it to the other. If one image in a pair was thought to possess a generally clearer atmospheric condition than the other (i.e. lower dew point in Table 1), it was used as the base image and the other was corrected to it. Otherwise the past image was corrected to the present one as a default.

Admittedly, this form of atmospheric correction may compromise this study's ability to accurately derive values pertaining to individual scenes, such as the city's absolute albedo in a given image. However, this method was found to be optimal for deriving the changes between image pairs – such as the change in citywide albedo over the test period – and, accordingly, it was found to give results with a higher degree of consistency than some physics-based correction techniques that were investigated.

This correction method was also applied to the radiance of the LANDSAT thermal bands since it was assumed that objects that did not undergo major surface changes during the test period should also have stable average surface temperatures. Like the reflectance, this means that the surface temperature values in this study are not precise indications of the actual surface temperatures of individual LANDSAT scenes. Rather, they are meant to capture the average temperature change from surface modifications during the test period.

Normalized difference vegetation index (NDVI) was calculated for all images using the corrected reflectance of LANDSAT bands 3 and 4 and a threshold NDVI of 0.35 was applied to all images to distinguish vegetated surfaces from non-vegetated ones. It is worth noting that this NDVI threshold value is fairly high for most studies and, as a result, a number of sparse lawns that did not have an NDVI as high as 0.35 were not classified as vegetated surfaces. However, this 0.35 value is justifiable by the fact that pixels with an NDVI below it did not exhibit a strong correlation between NDVI and temperature while those above it did. This trend is visible in Fig. 1 as well as a number of other studies that observe urban NDVI [13,26]. The high threshold is also justifiable in that, above 0.35, NDVI is agreed to have a strong correlation to photosynthetic activity and plant evapotranspiration [11]. Accordingly, NDVI can be used as a measure of quantity of vegetation within a pixel and not just a measure of how likely that a given pixel is vegetated.

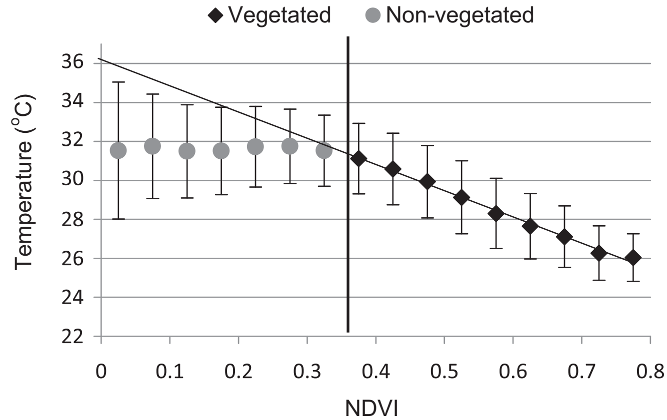

Fig. 1. The origin of the 0.35 NDVI threshold as illustrated by the relationship between NDVI and temperature in the image from May 30th 1995. Each data point represents a bin-averaged value with error bars indicating one standard deviation. The best fit line for values above 0.35 has a negative slope indicating cooling as NDVI increases while values below 0.35 are best fit by a flat line with no correlation. This trend of temperature decrease above a 0.35 NDVI is observable in all 8 Chicago scenes of this study.

Once the threshold was set, images of Chicago's NDVI in vegetated pixels (above the 0.35 threshold) were generated for each of the dates along with images of multi-band reflectance for non-vegetated pixels (below the 0.35 threshold). Images of multi-band reflectance then had their water pixels masked out after a supervised classification of such areas in each LANDSAT scene. Next, the multi-band reflectance images were converted into broadband albedo images using the formula developed by [15] for a band-weighted average albedo.

Temperature was calculated by using the inverse of the Planck function. An emissivity value of 0.954 was used in this function that was derived by averaging the values of all pixels within the Chicago political border of a July 2006 ASTER emissivity product. The images of NDVI and albedo were then laid over their corresponding temperature images and the relationships between the variables were assessed. Afterward, the pixel values of all 1995 images were subtracted from those of the corresponding present images to yield data sets for the change in albedo, NDVI, and temperature between 1995 and the present. The albedo change and NDVI change images were laid over their corresponding temperature change images and the relationships between them were assessed.

When evaluating the relationships between NDVI, albedo and the corresponding temperature, analysis was done on a pixel-by-pixel basis. For example, let a_p and b_p represent the albedo change and temperature change respectively at pixel p of an image pair. A negative correlation between a and b across the city would provide confirmation of the effectiveness of the albedo strategy since temperature decreases as albedo increases.

After this analysis, an attempt was made at verifying the causes of albedo and NDVI changes observed in the LANDSAT images using high resolution aerial photography from an April 1998 National Aerial Photography Program (NAPP) flyover and a June 2010 aerial flyover by the USDA Farm Service Agency. Aerial images were laid over images depicting change in LANDSAT data and specific areas of NDVI, albedo, and temperature change were identified. This last step verified that many of the instances with decreased temperature in the LANDSAT images were the result of efforts to reduce urban temperatures such as the installation of new reflective roofs, the zoning of new parks, and the planting of new street/yard trees.

3. Results

3.1. Correlations of NDVI and albedo to temperature within single scenes of Chicago

Before the selected LANDSAT data can be used to draw conclusions regarding the effectiveness of cooling strategies, it is first necessary to determine whether satellite-observed NDVI and albedo actually correspond to lower LANDSAT temperatures in individual scenes of Chicago. As Fig. 2 illustrates, both parameters exhibit inverse correlations to temperature and generate negatively sloped linear regressions in plots against temperature. This, along with Table 2, which displays the correlations and slopes of the 8 plots used to make Fig. 2, establishes that LANDSAT temperature in Chicago consistently decreases as NDVI and albedo increase.

Though NDVI and albedo share this trend, Chicago's vegetated NDVI has a much stronger relationship to lower temperature than its non-vegetated albedo. For example, NDVI above the 0.35 threshold consistently produces strong correlations around −0.67 while non-vegetated, non-water albedo consistently produces far weaker correlations around −0.15.In accordance with this, the linear regressions for NDVI/temperature plots consistently have steep slopes around −16.2 while those for albedo/temperature plots have shallow slopes around −6.9. Such a comparison of slopes is meaningful because both graphs in Fig. 2 portray similar ranges of both NDVI and albedo, which conveniently marks the approximate maximum and minimum of both parameters in the scenes of Chicago. Multiplying these similar ranges by the regression slopes grants a sense of the typical maximum cooling provided by each parameter within Chicago, translating to a maximum NDVI cooling around −6.5 °C and a maximum albedo cooling around −3.1 °C.

These sharp differences between NDVI and albedo seem consistent with the observations of previous studies that have used remote sensing to compare similar parameters to temperature within cities. For example, a study of 24 cities by Small [21] used a vegetation index to observe the strong inverse correlation between surface temperature and vegetation fraction that this study notes above through NDVI. Additionally Small [21], found the relationship between surface temperature and thermal rock substrate, which is related to non-vegetated albedo, to typically be much weaker and explained this through competing effects of albedo, illumination and soil moisture. Factors such as soil moisture, which darkens and cools surfaces, may also explain the weaker relationship between non-vegetated albedo and temperature observed here. Regardless of explanation, the consistency of these findings with studies of multiple cities suggests that these trends are common and are likely relevant to many other situations.

Table 2
The linear correlations and slopes of linear regressions for plots of NDVI and albedo against temperature in single scenes of Chicago.

Date	NDVI to temperature		Albedo to temperature	
	Regression slope	Correlation	Regression slope	Correlation
May 30th 1995	−13.2	−0.64	−5.1	−0.10
June 5th 2009	−16.6	−0.67	−11.4	−0.21
July 3rd 1996	−16.1	−0.69	−4.1	−0.12
July 2nd 2007	−16.7	−0.67	−11.2	−0.14
June 15th 1995	−16.9	−0.66	−4.2	−0.14
June 16th 2007	−18.9	−0.69	−7.4	−0.17
July 1st 1995	−17.0	−0.71	−6.6	−0.21
June 24th 2010	−14.2	−0.63	−5.0	−0.09
Average	**−16.2**	**−0.67**	**−6.9**	**−0.15**

3.2. Correlations of NDVI and albedo change to temperature change between paired images

In spite of the above trend emphasizing the cooling impact of vegetation over albedo, it appears that Chicago's increases in albedo during the test period were more effective at lowering LANDSAT surface temperatures than its increases in vegetation. Fig. 3 displays this by plotting the average albedo and NDVI increases of the 5 images pairs against the corresponding temperature changes over the test period. Table 3 displays the correlations and slopes of the individual plots used to make Fig. 3 and shows that the trends are consistent across the 5 images pairs. As both the figure and table illustrate, increases in non-vegetated non-water albedo had strong correlations to temperature decrease around −0.33 while increases in vegetated NDVI had weaker ones around −0.17. Similarly, the slopes of regressions for albedo increase/temperature change plots are steep around −15.7 while those for NDVI increase/temperature change plots are shallow around −8.9. Multiplied by the ranges of NDVI and albedo increase, this translates to a typical maximum albedo cooling of −6.3 °C and a typical maximum NDVI cooling of-3.6 °C.

Though Table 3 displays an acceptable degree of consistency between the correlations and regression slopes of the 5 image pairs, many of the disparities between them have reasonable explanations that strengthen the certainty of their accuracy. For example, the fact that Image pairs 1 and 5 have stronger correlations and steeper slopes for albedo increase than pairs 2, 3 and 4 makes sense in light of the fact that 1 and 5 use images from 2009 to 2010 to signify the present while the others use images from 2007. In 2008, Chicago's reflective roof zoning codes were intensified to require a higher minimum albedo for new roofs and this likely

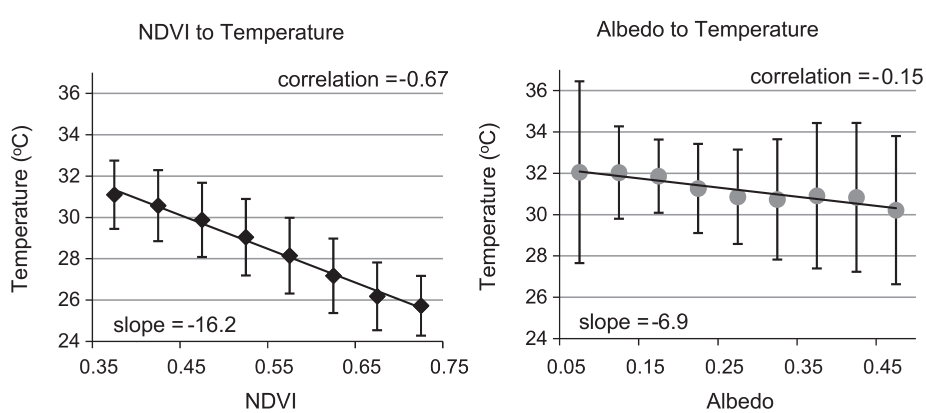

Fig. 2. Plots of NDVI and albedo against LANDSAT temperature depicting the average values and trends across all 8 images observed in the study. Each data point represents a bin-averaged value with error bars indicating one standard deviation.

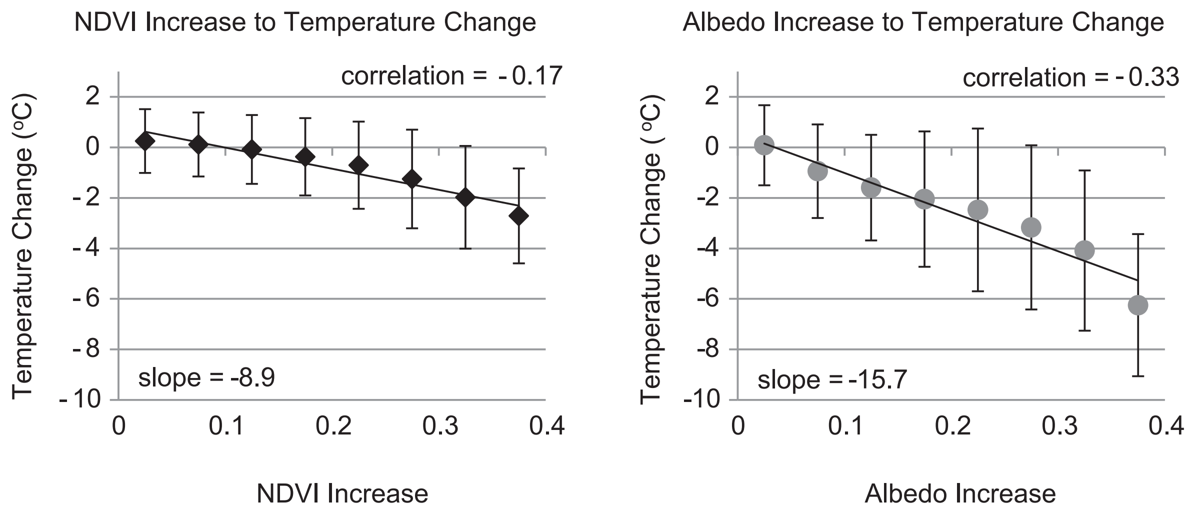

Fig. 3. Plots of NDVI and albedo increase against LANDSAT temperature change between 1995 and the present. Data points and regression curves depict the average values and trends across all 5 LANDSAT past/present pairs observed in the study. Each data point represents a bin-averaged value with error bars indicating one standard deviation.

strengthened the cooling effect of albedo increases in pairs using images after this policy change. Yet another disparity with a reasonable explanation is the unusually strong correlation (−0.32) and steep slope (−15.1) of image pair 5′s NDVI increase to temperature change. This anomaly is clarified in Table 1, which reveals that Image pair 5 has an unusually large disparity between the two images' previous rainfalls. Before the day that the image characterizing the present was taken in this pair, there was a substantial precipitation event of 3.1 cm that was not reciprocated in the past image. Also, the month before the present image's capture had a record-breaking quantity of rainfall around 18.6 cm while the past only received 8.1 cm. The additional rainfall in the present image must have intensified the cooling effects of the vegetation increases between the two dates by accelerating plant growth, productivity and evapotranspiration in a way that the minor precipitation disparities of the other pairs did not. Interestingly enough, this increased precipitation does not seem to have strengthened the correlation of the present image's overall NDVI to temperature within that one scene (−0.63) as this value is less than the average of all 8 scenes (−0.67). However, such precipitation has clearly had an effect on the NDVI increases between the dates and reveals that the cooling effects of Chicago's new vegetation are highly dependent upon rain. This finding has interesting consequences for cooling strategies that anticipate increases in precipitation from global warming since, in a scenario with increasing rain such as this, the cooling effects of new vegetation appear nearly equivalent to those of new reflective surfaces. However, for the purposes of understanding the optimal methods in the absence of changing precipitation conditions, the aforementioned trends stressing albedo cooling over NDVI cooling are valid and accurate.

Table 3
The linear correlations and slopes of linear regressions for plots of NDVI and albedo increase against temperature change over the test period.

Image pair	NDVI increase to temperature change		Albedo increase to temperature change	
	Regression slope	Correlation	Regression slope	Correlation
Pair 1	−7.0	−0.09	−21.1	−0.36
Pair 2	−5.9	−0.14	−10.1	−0.31
Pair 3	−9.8	−0.11	−17.2	−0.31
Pair 4	−6.8	−0.18	−11.8	−0.34
Pair 5	−15.1	−0.32	−18.5	−0.34
Average	**−8.9**	**−0.17**	**−15.7**	**−0.33**

3.3. *Changes in area of vegetated and reflective surfaces between paired images*

In addition to evaluating relationships between NDVI/albedo increases and temperature change, it is also useful to understand how much of the city's area was affected by such changes. One means of informing such an understanding is to consider the average quantities of LANDSAT pixels that increased in albedo and NDVI between the 5 image pairs. This reveals that there were approximately twice as many non-vegetated pixels that increased in albedo during the test period (300 579) as there were pixels that increased in NDVI to or above the 0.35 vegetation threshold (162 243). While informative, these quantities are not necessarily an indication that efforts to increase albedo influenced a larger area of the city since many of these pixels could be very close to a zero change between the two images and just happened to fall on the side of increase. One possible means of distinguishing the pixels that were effective efforts from the arbitrary increases is to eliminate the pixels that increased in albedo or NDVI by a value smaller than 0.01. This reveals an average of 142 367 pixels for NDVI and 216 581 pixels for albedo. Yet another means of distinguishing the cooling efforts is to only count pixels that increased in albedo/NDVI and also decreased in LANDSAT temperature and this method shows an average of 69 281 pixels for NDVI and 154 615pixels for albedo.

Perhaps the most informative way to understand the area cooled by each of the strategies is to multiply the area of pixels that increased in NDVI/albedo and decreased in temperature by the average cooling that was noted in these pixels. This would yield a general "area cooling index" for each method with the units of km$^{2\circ}$C. Following this process, NDVI increases exhibited an average area cooling index of 74.8 km^{2o}C while albedo increases had a much larger 214.6 km^{2o}C. An abstract way of understanding these values is to think of the cooling that occurred in Chicago as a region that had a uniform drop in temperature of 1 °C. In this sense, the area cooling index is the size of this region in km^2 that resulted from each of the methods.

3.4. *Changes in citywide NDVI and albedo*

With the exact area of the city that increased in albedo or NDVI still in question, it is worthwhile to inform this issue with observations of the citywide changes in these parameters over the test period. Table 4 displays such information and reveals a subtle increase in Chicago's average citywide NDVI around +0.009, which is mirrored by a small increase in vegetated surface area around +11.7 km^2. Although such an average increasing trend seems like a reasonable result of efforts to increase vegetation over the test period, this increase is inconsistent across the 5 image pairs and such a discrepancy must be explained in order for this inference to be acceptable. Notably, image pair 1 exhibits an almost nonexistent increase in citywide NDVI (+0.001) and a total decrease in Chicago's vegetated area (−5.8 km^2) that is contradictory to the overall increasing trend. The primary cause of this lack of consistency is likely the differences in precipitation before the images were taken, which can raise or lower the NDVI of surfaces by influencing plant productivity and photosynthesis. Such an explanation is supported by the general relationship between the pairs' previous-week precipitation difference and the citywide NDVI change, both of which are noted in Table 4. In this sense, the decreasing vegetated area of pair 1 is the result of a large decrease in the previous week's precipitation between the two dates. All image pairs support the trend of greater vegetation increase with an increase in previous-week rain except for Image Pair 4, which has the largest decrease in rainfall but also the greatest increase in NDVI of all the pairs. The reason for this anomaly is probably the 2.4% cloud cover in the past image of the pair (see Table 1), which sits directly above one of the largest areas of vegetation clearing that occurred during the test period. After this cleared area was masked in both the present and past images as part of the procedure, the citywide NDVI increase was recorded to be much greater than what actually happened over the whole city and, accordingly, this pair is not suitable for documenting the city's overall NDVI change. However, all other observations of pair 4 in this study should be valid as this section is the only one where vegetation decreases between dates play a role. Discounting this pair, the average NDVI change of the entire city is +0.007 and the average change in vegetated surfaces is +9.4 km^2. Since these 4 remaining pairs encompass a diverse enough number of precipitation scenarios, their average values of vegetation change are hopefully a good reflection of the terrestrial alterations that occurred during the test period and do not heavily reflect the changing rain conditions. Some reassurance of this can be found in the average change of previous week's rain among the 4 pairs (+0.62 cm), which is close to zero.

Contrary to the subtle effects of vegetation increases that are difficult to distinguish amid rain and cloud cover, Chicago's new reflective surfaces had a clear impact on the albedo of the city. All 5 pairs exhibit an increase in Chicago's citywide albedo that averages out to 0.016 and translates to 0.022 when one narrows down the domain to just the city's non-vegetated and non-water pixels. The area covered by pixels with albedo above 0.2 also increased by an average of 51.9 km^2, which is noteworthy because 0.2 is approximately the minimum albedo of a reflective roof. Though these findings exhibit a more certain trend than the NDVI increases, there is still a degree of inconsistency between the pairs in Table 4 that should be addressed. An important factor that likely accounts for the much higher albedo increase in pairs 1 and 5 is the aforementioned intensification of reflective roof zoning codes in 2008, which raised the albedo of the present images of these pairs (taken in 2009 and 2010) above that of the other pairs (taken in 2007). In this sense, the aforementioned average albedo increases are an indication of the change as of approximately 2008 and albedo seems to have continued to increase after this time. Yet another factor that likely contributes to the inconsistency is the effect that varying precipitation between the images has on soil albedo. As is the case with NDVI, the diversity of precipitation scenarios between the image pairs should be enough to counteract this error in the averages noted here.

The average albedo increase of 0.016 can also help give a sense of the change in the city's heat absorption that occurred over test period. For example, a citywide albedo increase of 0.016 means that an additional 3.9 W/m^2 are reflected away from the surface of Chicago during the months of June, July and August. This translates to an average reflection of 2.4 GW over the entire city during this time. To put this estimate in more tangible terms, this is the equivalent cooling power of approximately 65 000 large window air conditioning units operating non-stop at full capacity throughout these months or more than one extra air conditioning

Table 4
Parameters describing the citywide changes in Chicago's NDVI and albedo between past/resent image pairs. "Vegetated" and "Non-vegetated" refer to pixels above and below the 0.35 NDVI threshold respectively. All values come from LANDSAT data except for the previous week's rainfall, which was calculated using airport records.

Date	Whole city NDVI	Veg. area (km^2)	Veg. % of city	Whole city albedo	Non-veg. albedo	Area w/Albedo >0.2 (km^2)	Prev. week's rainfall (cm)
Image Pair 1							
May 30th 1995	0.295	222.3	36.6	0.152	0.153	21.0	5.1
June 5th 2009	0.296	216.5	35.6	0.173	0.180	84.4	2.3
Change	**+0.001**	**−5.8**	**−1.0**	**+0.021**	**+0.027**	**+63.4**	**−2.8**
Image Pair 2							
July 3rd 1996	0.270	177.5	29.7	0.159	0.160	29.1	0.0
July 2nd 2007	0.278	190.7	31.9	0.168	0.173	61.4	0.5
Change	**+0.008**	**+13.2**	**+2.2**	**+0.009**	**+0.013**	**+32.3**	**+0.5**
Image Pair 3							
June 15th 1995	0.277	185.5	30.5	0.156	0.156	23.9	0.5
June 16th 2007	0.284	196.0	32.3	0.172	0.178	73.0	0.0
Change	**+0.007**	**+10.5**	**+1.8**	**+0.016**	**+0.022**	**+49.1**	**−0.5**
Image Pair 4							
July 1st 1995	0.263	166.4	28.0	0.156	0.157	24.9	4.3
July 2nd 2007	0.277	187.4	31.6	0.168	0.174	65.0	0.5
Change	**+0.014**	**+21.0**	**+3.6**	**+0.012**	**+0.017**	**+40.1**	**−3.8**
Image Pair 5							
June 15th 1995	0.276	177.8	30.5	0.156	0.157	23.5	0.5
June 24th 2010	0.289	197.6	33.9	0.181	0.187	98.4	5.8
Change	**+0.013**	**+19.8**	**+3.4**	**+0.025**	**+0.030**	**+74.9**	**+5.3**
Average							
1995	0.276	185.9	31.1	0.156	0.157	24.5	2.1
Present	0.285	197.6	33.0	0.172	0.178	76.4	1.8
Change	**+0.009**	**+11.7**	**+1.9**	**+0.016**	**+0.022**	**+51.9**	**−0.3**

for every two households. Of course, it is important to keep in mind that this cooling is diffused whereas air conditioners act on specific rooms but this quantity nevertheless suggests that reflective efforts produced a large enough effect to impact microclimates, especially in some neighborhoods where albedo increases were found to be as much as four times that of the city average.

3.5. Changes on building to neighborhood scales

In an attempt to verify that the NDVI and albedo changes observed in the previous sections were the result of at least partially-intentional urban cooling efforts, high resolution aerial images taken in 1998 and 2010 were analyzed in relation the LANDSAT data. To accomplish this, LANDSAT-derived images were generated in which areas of increased and decreased NDVI, albedo and temperature could be easily located (Fig. 4). Areas of apparent albedo and NDVI increase were observed in relation to the aerial images and specific instances that represent the effects of certain methods were selected for display in Fig. 5. For this figure, an attempt was made at finding instances that best characterized the citywide impacts of each of four different types of cooling efforts employed by Chicago in the test period: reflective roofs, green roofs, street trees, and green spaces (i.e. parks, grassy schoolyards, and nature preserves).

LANDSAT temperature changes resulting from new reflective roofs were some of the largest of those observed in the study. Certain multi-block neighborhoods, such as the Western Ukrainian Village depicted at the top of Fig. 5, were found to have cooled by as much as 3.4 °C with albedo increases around 0.07. Some large warehouse roofs that became reflective, such as the one on the Industrial Storage Warehouse Corporation on W Ohio Street (second row of Fig. 5), cooled by as much as 5.0 °C with albedo increases around 0.16. It is worth noting that a large fraction of the areas of albedo increase in Fig. 5(the green areas) were found to be the result of reflective roofs. From simple visual observations, more than 75% of the “green areas” in Fig. 5 can be attributed to new reflective roofs and most of the remaining changes appear to be the result of new bare soil or the weathering of asphalt. Accordingly, this effort had a definite cooling impact that was widespread and likely affected the LANDSAT heat island of the city.

Green roofs were admittedly difficult to evaluate using this method since many of the new instances that were larger than a 30 m pixel were installed over new skyscrapers in the downtown region where bare soil had existed previously. In spite of this, there are a few striking trends in the LANDSAT images that reveal the effectiveness of this strategy. Most importantly, out of 21 new green roofs larger than a 30 m pixel that were identified in the downtown area, not a single one succeeded in producing a LANDSAT pixel with an NDVI greater than 0.35 in any of the images of this study. As noted in Fig. 1 and other studies [13,26]; the surpassing of this threshold is necessary for a vegetated surface to produce noticeable cooling effects and suggests that the green roofs were ineffective at lowering LANDSAT temperature over the test period. The third row of Fig. 5 supports this inference with observations of one of the few large green roofs that arose over an existing building in the test period: the new green roof atop City Hall. As the figure illustrates, the new vegetation over this 120 m × 60 m surface fails to produce any 30 m-pixels that pass the 0.35 threshold and instead shows up as an albedo increase of 0.02 in the LANDSAT images. In accordance with this, an insignificant average LANDSAT temperature change of −0.1 °C occurs over the roof.

The failure of the green roofs in this manner is surprising and, as other instances of cooling efforts will reveal, grass at ground level easily passes the vegetation threshold and produces noticeable LANDSAT cooling. Accordingly, there appears to be a consistent difficulty in getting vegetation to be dense enough in the layer of soil on building roofs such that there are noticeable effects on the LANDSAT scale. It can thus be concluded that this type of effort had an insignificant effect on Chicago’s LANDSAT heat island and this is especially true when one considers that all of the city’s new green roofs account for at most 7 million square feet of additional vegetation, which is approximately one thousandth of the city’s total area.

Unlike new green roofs, certain multi-block neighborhoods with new street trees exhibited strong indications of cooling. The fourth row of Fig. 5 is a good example of this trend and depicts a neighborhood where increases in NDVI were primarily the result of new trees: the blocks bounded by Garfield Boulevard, Ashland Avenue, 51st Street, and the rail yards of the New City Community Area. Here, areas of NDVI increase from new trees in the NDVI-change image seem to be mirrored by areas of temperature decrease in

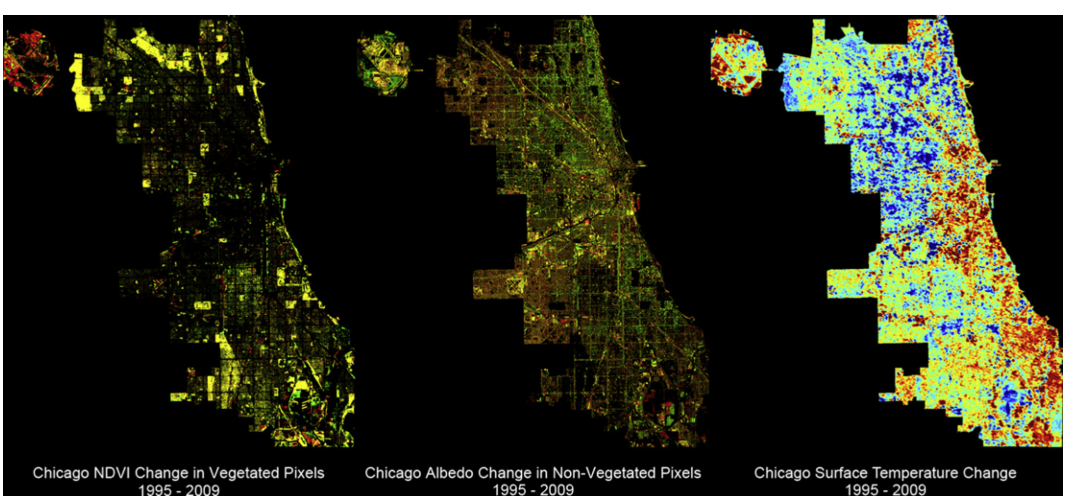

Fig. 4. Images used to identify areas of NDVI, albedo and temperature change for comparison with aerial images. Albedo and NDVI change images depict LANDSAT data of each parameter from 1995 set to a red channel and from 2009 set to a green channel. Thus, an area appears greener if it increased in the given parameter over the test period and redder if it decreased. Yellow, brown and black signify minimal change. The temperature change image is a color coded subtraction of 1995 temperature from present day temperature. The darkest blue denotes a decrease in temperature by 3 °C while the darkest red is an increase in temperature by 3 °C. Original LANDSAT images for this figure are taken from image pair 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

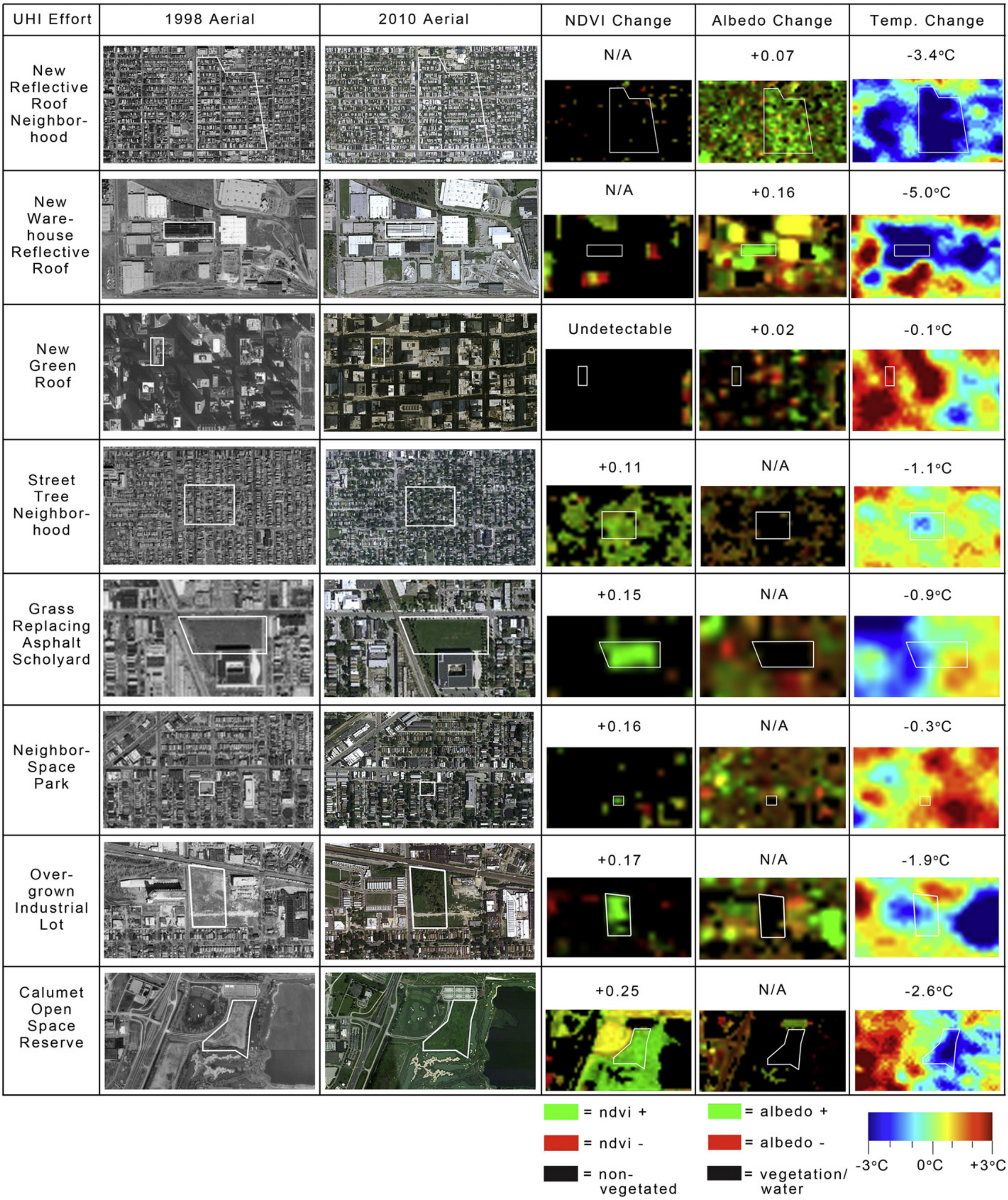

Fig. 5. Specific examples of UHI efforts during the test period. The two left columns contain high resolution aerial images while the three right columns show enlarged and resampled versions of the LANDSAT images in Fig. 5. Quantities above the images in the three right hand columns represent the change in the area bounded by the white lines averaged across all 5 image pairs. Note: NDVI change values only account for the portion of the change above the 0.35 threshold.

the LANDSAT thermal image. Also, when zoomed in to specific blocks of particularly intensive tree planting (bounded by the white box), cooling trends around −1.1 °C are apparent amid NDVI increases of 0.11. In light of this and the fact that Chicago increased its tree count by at least 15% during the test period, it seems likely that the trees had a cooling effect on Chicago's LANDSAT UHI. This effect was larger than that of green roofs but does not appear to be as influential as the reflective roof zoning.

New green spaces produced the most varied results of all the cooling techniques observed because they encompass a large range of sub-methods including the replacement of asphalt schoolyards with grass, the zoning of new community parks, and the establishment of new nature preserves. The conversion of schoolyards from blacktop to grass produced noticeable results in LANDSAT imagery, which appear comparable in cooling and NDVI change to blocks of intense street-tree planting. For instance, the conversion of the playing field at Ames Middle School (fifth row of Fig. 5) cooled the area by approximately 0.9 °C while increasing NDVI by 0.15. Considering that Chicago converted over 100 of such schoolyards in the test period, it seems likely that this strategy had a modest cooling effect.

Many of the areas that were identified as the city's newly-zoned parks were sub-block-sized sites such as the McKinley Library Park in the sixth row of Fig. 5. As the figure suggests, these strategies were large enough to produce noticeable changes in single 30 m-pixels of the NDVI change images but had relatively insignificant effects on the thermal images, which were captured using LANDSAT 5′s 120 m-pixel thermal thematic mapper. Consequently, the park in Fig. 5 exhibited a large NDVI increase of 0.15 but a temperature change of only −0.3 °C. Although this study's method of evaluation is not ideal for determining the effects of such small parks, it seems safe to conclude that these parks had a minor citywide cooling impact. This is especially true when one considers that there were over 100 similar new green spaces that arose during the test period which, when taken together, would amount to a large area exhibiting noticeable LANDSAT cooling.

A collection of new vegetated areas that proved much more noticeable than these identified parks was a number of slightly larger industrial lots that became abandoned and overgrown in the test period. If action were to be taken to allow these newly vegetated areas to be left intact, then this strategy could certainly be considered an effective method for cooling and reducing urban temperatures. A good example of one such site is a lot next to an abandoned warehouse with the address 1856 N Leclaire Ave. (eighth row of Fig. 5). As the figure illustrates, the NDVI of the lot increased by 0.17, triggering a substantial drop in temperature around 1.9 °C. An exact count of these sites was difficult to assemble but they seem least as common as converted schoolyards and they had more intense cooling effects than these schoolyards.

The largest cooling from vegetation was a previously industrial site around the recently established Calumet Open Space Reserve (last row of Fig. 5). With this site seemingly left to return to levels of native vegetation, the area cooled by 2.6 °C with an overall NDVI increase of 0.25. Although there is only one of these reserve-scale areas that arose in the test period, this instance establishes a compelling argument for large parks/reserves as the vegetation-based strategy that is the most effective at cooling.

4. Discussion

Before the findings of this study can inform planning decisions and urban cooling strategy, it is first necessary to consider a few limitations of the data set. Perhaps most importantly, this study relies almost entirely on data from LANDSAT 5, which has several limitations in terms of the accuracy of albedo, NDVI and temperature values that are derived from it.

Firstly, the albedo values that were generated in this study do not take into account the hemispherical reflectance of surfaces in the manner that some of today's sensors can and, accordingly, albedo values only indicate the changes at specific sensor and sun angles for each image or pair. MODIS bi-directional albedo products, which are much better at describing this hemispherical albedo, give generally lower values for the citywide albedo of Chicago that are around 0.13 (the LANDSAT values of this study are around 0.17). Also, the citywide MODIS albedo increase between 2002 and the 2010 is around 0.006, which suggests that the average citywide increase in LANDSAT albedo between 1995 and the present (0.016) may be slightly lower when one considers hemispherical effects. This inaccuracy is not enough to undermine the general trends that the LANDSAT albedo demonstrates, such as its correlation to temperature or the fact that it noticeably increased over the city during the test period. However, it does throw into question the exact albedo values of the study and the information that is derived from them.

Another limitation of the older LANDSAT 5 data in this study is that it is difficult to obtain several atmospheric profiles to correct for the effect that the atmosphere has on the thermal radiance reaching the sensor. More explicitly, the formulas for temperature calculation in this study do not account for the radiation that is inevitably lost through the small amounts of humidity and aerosols in a clear-sky atmosphere and so the actual surface temperature values are slightly higher than those listed here. The atmospheric correction performed in this study accounts only for the atmospheric differences between image pairs based on the matching of stable surfaces and does not account for the amount of radiation lost to a clear-sky atmosphere. Thus, if a complete physics-based atmospheric correction with on-site balloon sounding data were applied to the LANDSAT images, it would likely shift all calculated temperature values up by a few degrees depending on the humidity and aerosols in the atmosphere [3]. Based on observations of the present day images of the study, for which there was sufficient sounding data, temperature values were shifted up by an average of 6 °C although this varied by one or two degrees depending upon the image.

A third major limitation is that only one emissivity value of 0.954 was used to derive surface temperature values for the entire city. In order to understand the error that this might generate, an ASTER emissivity product of Chicago in July 2006 was analyzed, which revealed a tendency for emissivity to slightly increase as NDVI increased and decrease as albedo increased. This resulted in a temperature error of as much as ±1 °C for the highest albedo and NDVI pixels respectively (Fig. 6). The regression curves derived from the ASTER product in Fig. 6 can be used to correct some of the trends observed in the LANDSAT images, such as those displayed in Fig. 2. With this correction, the average correlation between NDVI and temperature in single scenes is slightly more negative around −0.71 (originally −0.67) and the correlation between albedo and temperature is slightly less negative around −0.10 (originally −0.15). Applying these same regressions to the NDVI and albedo change plots of Fig. 3 may generate misleading results because the changes in NDVI and albedo over the last 15 years are different than these absolute parameters across the city. However, it is at least good to know that this study's primary conclusions still hold in the application of these regressions. For example, albedo increases still have a stronger correlation to temperature decrease (−0.29) than NDVI increases (−0.23). Additionally, albedo increases still have stepper slopes in plots against temperature change (−12.8) than NDVI increases do (−10.2). Furthermore, the "area cooling index" that was described in Section 3.4 is still greater for albedo (227.2km^{2o}C) than it is for NDVI (75.5km^{2o}C).

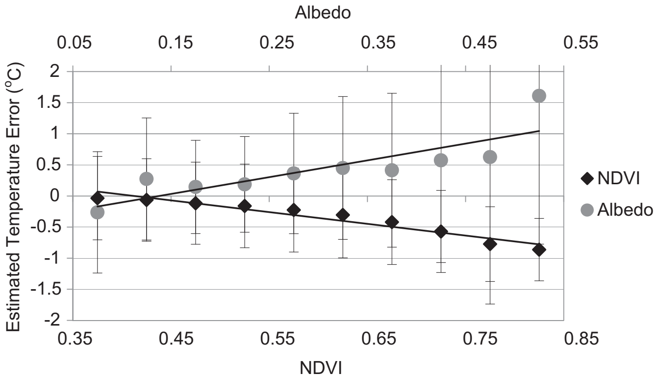

Fig. 6. NDVI and albedo plotted against estimated temperature error resulting from differing emissivity in a 2006 ASTER image of Chicago. Estimated temperature error was derived using the Planck function with emissivities taken from the ASTER image in the LANDSAT TM thermal wavelength and temperature from the average LANDSAT surface temperature across the 8 images in this study (304.4 K).

In addition to the limitations of the LANDSAT 5 sensor, there are also general limitations in using any form of remotely-sensed data to draw conclusions about the effects of surface changes on humans. Notably, satellite data tends to over sample typically uninhabited places such as rooftops, treetops and roads while under sampling the places people usually occupy such as sidewalks, the spaces beneath trees and rooms beneath roofs. Consequently, there is a great deal of uncertainty when attempting to evaluate how exactly these remotely-sensed temperature changes will affect the inhabitants of Chicago.

In spite of this ambiguity, this study can provide relatively reliable conclusions regarding the impact of these methods on nighttime air temperature. This is because surfaces that retain more heat during the day will release more heat at night, warming the inhabited areas around the typically uninhabited rooftops, treetops, and roads. Arguably, this process is one of many that generate the clearer citywide heat island observed at night, as the heat held by particular urban surfaces with high thermal retention capacities disperses. Thus, the general air temperature of Chicago's neighborhoods at night is correlated to the heat that specific surfaces retain during the day. The heat stored by these surfaces is often correlated to their daytime temperature unless one is considering the effects of water bodies or street canyons, which store a lot of heat but do not register very high daytime LANDSAT temperatures. Considering that street canyons and water bodies remained mostly stable during the test period, changes in LANDSAT temperature likely resulted from surface property modifications such as albedo and vegetation cover changes. Consequently, the daytime LANDSAT surface temperature changes observed in this study are likely related to similar changes in Chicago's nighttime air temperature and it is through this lens that the effect of these surface modifications on humans can be evaluated.

In light of this, the findings of this study are much more practical when they are applied to the night-time UHI and its effects. This may add more meaning to the findings since most heat-related deaths occur at night [9] and nighttime is arguably the period of the day when thermal comfort is most needed in order to induce sleep. A greater emphasis on nighttime effects also means that inhabitant behavior patterns are more predictable since most citizens will be sleeping in their residences at this time. This underscores the efforts that are often closest to these residences such as reflective roofs, green roofs and sometimes street/yard trees, while deemphasizing those efforts that are often further away, such as green spaces.

5. Conclusion

Taken together, the results present a compelling argument for reflective cooling strategies over the vegetative. The impact of Chicago's reflective increases in the test period surpassed those of vegetation in terms of the number of pixels that they cooled, the clarity of their effect on the whole city, and the strength of their correlation to lower temperatures. Aerial image analysis confirmed that reflective roofs were responsible for a large fraction of albedo increases in the test period and closer observations showed these roofs were responsible for some of the greatest cooling trends of all observed methods.

Accordingly, cities similar to Chicago in climate, population and economic situation that wish to reduce their temperatures should consider making reflective efforts a critical point of their strategies. Specifically, reflective roofs have proven themselves effective and this is likely because they provided the greatest amount of cooling for the smallest amount of money invested. Vegetation that is dense enough to provide desired cooling seems to have high installation and maintenance costs that prevent it from having the same widespread cooling effects of reflective roofs. Also, the fact that new vegetation often replaces moist soil, an already cool surface, means its impact is diminished in relation to reflective roofs, which are typically installed over dark impermeable surfaces.

In spite of these findings in favor of reflective roofs, this does not mean that vegetation-based strategies should be disregarded. It is important to remember that NDVI in single scenes of Chicago exhibited the highest linear correlation to lower temperature out of any in this study and this hints at an enormous potential for cooling if vegetation can be installed to a great enough density. Perhaps a cooling strategy is not subject to economic concerns would place a high priority on the planting of vegetation to reach an ideal minimization of its UHI. This notion of the ideal vegetated city is also supported by the additional benefits that vegetation brings over reflective surfaces, such as reduced storm water runoff and a number of other ecosystem services.

In summary, while a vegetated strategy may be effective over the span of several decades in cities with plentiful funding for cooling efforts, Chicago's reflective strategies were much more effective at cooling the city over the last 15 years and likely denote a more effective strategy over such a time period for today's temperature metropolises.

Role of the funding source

This study was supported by Yale University. The sponsor had no role in the design of the study; in the collection, analysis or interpretation of data; in the writing of the report; or in the decision to submit the paper for publication.

Acknowledgments

The Yale Center for Earth Observation, the Yale Department of Geology and Geophysics, the Yale Remote Sensing Heat Budget Group, and Laurent Bonneau.

Appendix. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.buildenv.2011.08.004.

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