An analysis of the relationship between land surface temperature and land use/cover over time in Travis County, Texas

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Abstract

Travis County, Texas has experienced a relatively rapid expansion over the past three decades, a trend which is expected to increase with time. Such urbanization and industrialization contributes to a distinct urban climate known as the urban heat island (UHI), where land surface temperatures are hotter in urban areas compared to its surroundings. The adverse consequences of which can include the deterioration of living environment, increased energy consumption, elevated ground-level ozone, and even an increase in mortality rates (Memon et al 2008). This study integrates remote sensing and geographic information systems (GIS) for detecting urban growth and assessing its impact on surface temperature in Travis County by using Landsat Thematic Mapper data and National Land Cover Data from 2001 and 2011. Detecting land surface change over time required relativizing temperature of the study area by the temperature of persistently cold areas on the days considered in this analysis. This study showed that the Travis County has increased by an average of 2.43°C between 2001 and 2011. Land classified as urban in 2011 increased an average of 2.38°C and agricultural land (hay/pasture, herbaceous, and cultivated crops) in 2011 increased in temperature by 4.26°C. The methods used to assess surface temperature change over time were successful and are worthy of continued application to derive more historical trends in temperature change over time.

Introduction

Urban landscapes are distinct from their encompassing environment in a number of ways, one of which is a distinct climate. Due to the heat generated from urban structures (as they consume and reradiate solar radiations) and the additional heat sources from anthropogenic activities, urban areas often exhibit higher temperatures relative to its surroundings (Memon et al 2008). Additionally, land use transitions to development typically result in significantly decreased vegetation or canopy cover, which decreases the land's heat reducing capacity. These features of urban landscapes culminate into what is known as the urban heat island (UHI) effect; the adverse consequences of which can include the deterioration of living environment, increased energy consumption, elevated ground-level ozone, and even an increase in mortality rates (Memon et al 2008). Rapidly growing and developing cities stand the most to gain from studies investigating trends in UHI, as the results can inform UHI mitigation efforts.

Such investigations have involved the integration of remote sensing and geographic information systems (GIS) for detecting urban growth and assessing its impact on surface temperature in the region (Weng 1999). Land surface temperature (LST) is derived using Landsat TM and/or ETM+ thermal band data. Studies that took place prior to when Surface Reflectance Climate Data Record (CDR) software was available processed the thermal band satellite images to convert the digital number into radiant temperatures (Weng 1999) or by using pre-launch calibration constants (Mallick et al 2008). Because it is not possible to directly compare raw temperature across multiple time periods, studies interested in understanding how LST of urban areas has changed over time focus on UHI intensity and its spatial patterns over time instead (Chen et al. 2006). UHI intensity is measured as the difference between peak temperature found inside the urban area and the background rural temperature (Chen et al. 2006; Memon et al 2009). To relate temperature to land cover, Chen et al (2006) used a suite of indices derived from the satellite images, including normalized difference vegetation, wetness, bareness, and built-up indices. The results from this study, which took place in Southern China, were negative correlations between the vegetation, wetness, and bareness indices and temperature when vegetation is limited in range, but positive between the built up index and temperature. Weng (1999) used a supervised classification technique with the maximum likelihood algorithm to classify the Landsat images. They also produced a change matrix for land use/cover change detection. This study, which took place in Zhujiang Delta, China, found that urban development had raised surface radiant temperature by 13.01 K in the urbanized area.

The objective of this study is two-fold: (1) to create a map of land surface temperature change from 2001 to 2011 in Travis County, Texas, and (2) to relate changes in temperature to changes in land cover types.

The city of Austin, located in south central Texas, is the 11th-largest city in the United States and was the third-fastest-growing large city from 2000 to 2006 (US Census Bureau Newsroom 2013). This makes Austin an attractive area to consider urban impacts on climate. Austin counties include Travis, Williamson, and Hays. Only Travis County, which covers an area of approximately 2,650 km^2, encompasses downtown Austin as well as the more recently developed area surrounding Lake Travis, was considered in this analysis **(Figure 1).**

Data

Instead of classifying the satellite images, I used USGS National Land Cover Data (NLCD). This limited the time period considered in this study, because the longest range of NLCD available is from 2001 to 2011. The land cover data was necessary not only to relate changes in temperature to changes in land cover over time, but also to process the thermal images. According to Wickham et al (2010), NLCD 2001 overall Anderson Level II and Level I accuracies were 78.7% and 85.3% respectively. Accuracy assessments for 2011 are not currently available, however any error in classification of NLCD will be inherent in this analysis.

With regards to satellite images, I used Landsat 5 TM images for path 27, row 39 that were taken on Oct. 17, 2001 and Oct. 29, 2011. Choosing images that were taken during the same season limits the amount of temperature as well as phenology variation throughout the year. In addition, the images selected were unimpeded by cloud cover (0%). The thermal infrared band (band 6) for Landsat 5 images has a spatial resolution of 120 m but is resampled to 30 m resolution. I used the service provided by USGS Landsat Surface Climate Data Record, which converts the raw values from band 6 TM images to brightness temperatures. As a result, temperature is reported in Kelvin and multiplied by 100 to produce integer values.

Methods

Land Surface Temperature Change

I conducted all spatial analysis in the UTM Zone 14 Northern Hemisphere projection. The fundamental procedure I used for evaluating change in land surface temperature was to relativize temperature for both images, so that the values are temperature difference between the coldest and hottest areas. This is similar to the methods used in Chen et al (2006) and Memon et al (2009), however is unique in that comparisons are of persistently cold areas instead of rural areas. Subtracting these images from each other results in relative temperature change from 2001 to 2011. To do this, I first had to set the extent of the thermal image to the extent of Travis County. Viewing this image with a histogram equalization stretch revealed that the water body itself is relatively warm, and in some areas, has the highest values of the entire study area. Because the physical properties of water cause it to heat up at a slower rate than land surface and also retain heat longer, temperature reported in the thermal image of the surface of water would be confounding. For this reason, I removed pixels classified as water in the NLCD images from the thermal images. I then identified the coldest 5% of the study area for both of the images. I retained only those pixels that were among the coldest 5% for *both* of the images and calculated the average temperature of those pixels for each image. I subtracted this value from the entire thermal image to produce the magnitude of difference from the coldest areas – the relativized land surface temperature change for the study area between 2001 and 2011. I converted the values to Celsius temperature values using Eq. (1), in order to make the results more interpretable.

$$C = (\text{Value} - 273.15) / 100. \tag{1}$$

Land Cover Change

A quick visual inspection of the land surface temperature change layer revealed that areas with the greatest increase in temperature were correlated with not only urban land as expected, but also areas classified in the NLCD layer as cultivated crops, hay/pasture, and herbaceous (collectively considered as agricultural land cover in this analysis). In order to quantitatively ascertain the contribution of changes in these cover types to the changes in temperature, I created a layer of just developed pixels, as classified by the NLCD (21, 22, 23, and 24) and another layer of just agricultural cover pixels (81 and 82) for both of the images. From these two images, I retained only "new" pixels that were absent in 2001 and present in 2011. I assigned values of temperature change to both of these layers by multiplying them by the change in land surface temperature layer produced from the methods detailed in the previously. I calculated the weighted average of the temperature change value for these two categories of pixels. The result is an approximation of the amount of increased temperature associated with urban and agricultural land. Similarly, I assessed the temperature change of *all* of the land classified as urban or agricultural cover in 2011. This enabled comparisons between preexisting urban or agricultural cover and those that existed prior to 2001.

Results

The raw temperature, shown in **Figure 2** reveals that Travis County was colder on Oct. 17, 2001 (ranging from -1.89 °C to 24.79 °C, Fig 2a) than the temperature on Oct. 29, 2011 (ranging from 1.24°C to 32.92°C, Fig 2b). These images also reveal general temperature trends within the study area: temperatures are hottest on the West side of the county, which corresponds to areas of higher density development as well as agricultural land, while the areas closer to the Lake Travis (and subsequently areas with more topographic variation), are generally cooler.

Figure 3 shows the spatial pattern of the 5% coldest pixels of the study area for both of the images. This was 5.3% of the study area in 2001 and 4.2% of the study area in 2011. There was a great deal of overlap in the distribution of these pixels: a total of 3% of the study area was coldest in both of the images. In 2001, temperatures were coldest both north and south of the river, while in 2011, temperatures were colder primarily north of the river. For this reason, only those "persistently cold" pixels (that were coldest in both images) were used to relativize the study area for each year. In 2001, the average temperature of these pixels was 11.04 °C and 12.77 °C in 2011. Subtracting these values from the respective thermal image, results in the primary product of this analysis (**Figure 4**). Travis County as a whole increased by an average of 2.43°C (**Table 1**). **Figure 5a** shows the distribution of temperature change from 2001 to 2011. All land classified as urban in 2011 increased an average of 2.38°C, while agricultural land (hay/pasture cultivated crops, and herbaceous) in 2011 increased in temperature by 4.26°C.

The most common land cover types in Travis County included evergreen forest, shrub/scrub, developed open space, and herbaceous. Those cover types that decreased the most from 2001 to 2011 were evergreen forest (-1.7%) and shrub/scrub (-1.2%). Those that increased the most include medium-density developed (2.3%), low-intensity developed (1.2%), and high-density developed (0.6%) (**Table 2**). Only changes in development and agricultural land were considered in this analysis. Between 2001 and 2011, an area of approximately 106 km^2 was developed. Three times this area (302 km^2) was classified as cultivated crops, herbaceous or pasture/hay (agricultural cover) in 2011 that was not classified as such in 2001. These changes in land cover equate to approximately 15% of the study area (**Figure 6**). The temperature change from new urban development was approximately 3.3 °C (**Figure 5b**) and 3.5 °C (**Figure 5c**) for new agricultural vegetation cover. Change in the developed cover types explained only 4% of the areas that increased in by 6 – 9 °C, while changes in agriculture-classified cover accounted for 28% (**Table 3**). The remaining 69% of the high temperature change pixels (that are not explained by these two change in cover classes) are displayed in **Figure 7a**. Evidence that this is not a valid assessment of the accuracy of the change in temperature surface is provided in the next section.

Discussion

The best way to improve the accuracy of this analysis, in regards to relating temperature to land cover change, would have been to classify the thermal images themselves into cover types, as opposed to using the NLCD for the year. This is because changes in land cover that occurred before the NLCD classification took place would result in "unexplained" change in surface temperature. In fact evidence that **Table 3** is not an accurate assessment of the effects of urbanization is shown in **Figure 7b**. This figure shows examples of some areas of "unexplained" temperature increase that are in fact likely explained by pre-NLCD classification development. Some striking examples include the Mosaic at Mueller apartments in downtown Austin, as well as the Omni at Barton Springs Golf Center **Figure 7c.** I was unable to contact staff at the Mosaic at Mueller apartment to confirm that the establishment of this complex occurred some time between 2001 and 2011, though this is likely the case. The golf course, on the other hand, was established in the early 80s. However, after speaking with staff, I was able to confirm that there have been recent additions to the golf course. Again, classifying the thermal images themselves would remedy such error.

There were some obvious "new" urban areas, as classified by the NLCD that were successfully picked up in the temperature change surface (**Figure 8**). Take for example State Highway 130 (SH 130), which was constructed and opened to traffic between 2006 and 2008, and 40-mile extension of SH 130 began construction in 2007 and opened in 2012. The land surface temperature change map captured the heat associated with this highway. Another example is the Stone Hill Town Center and surrounding residential neighborhood in Pflugerville.

There were also areas that did not change in land cover type, but were still areas of significant increase in temperature, which brings up another possible use of the surface produced in this analysis – the effect of anthropogenic activities on temperature. Areas where amount of urban land has stayed the same but where there was also an increase in temperature may be an indication of increased population or activities that result in higher temperature, such as increased automobile exhaust from traffic congestion or emissions from heating and cooling systems. For example, the Austin-Bergstrom International airport showed up as hotter in 2011 than in 2001. It is possible that, since the image taken in 2001 was on a Wednesday and the image taken in 2011 was on a Saturday, the change in temperature is actually a reflection of the weekend being more heavily traveled.

This analysis began as an attempt to determine the intensity of urban heat islands, however changes in land cover to more agricultural areas was revealed to also create heat islands. There was a significant amount of the latter land cover types that was associated with an increase in temperature over time but did not change in their land cover classification. The reason for this cannot be attributed to increased population or anthropogenic activities, but it could be related to changes in agricultural practices such as crop rotations, irrigation, or other factors that could cause temperature variation. It is important to note that more refined results would have been obtained by doing each land cover separately, instead of collectively considering them as agriculture. However, these land cover types had very similar spatial distributions, so the collective classification was appropriate for the scope of this analysis. Shrub/scrub land cover types also appeared to result in increased relative temperature, and could increase the amount of "explained" temperature change due to land cover change, though methods used in this paper would need to be repeated for this cover types in order to confirm this claim.

These methods proved to be successful in determining relative changes in temperature over one decade, suggesting that the application of these methods over a longer time span would be profoundly rewarding. While the core of Austin urbanized before 1970, a significant proportion has urbanized since the 1980s. Landsat 5 imagery is available from the early 1980s, so increases in temperature as a result of such development should be revealed through applying these methods. By doing 5-year intervals of temperature change, the persistently cold pixels would be refined and would likely provide more robust results.

Another worthwhile endeavor would have been to consider percent-developed imperviousness and tree canopy cover change, as these are two main contributing factors to a distinct urban climate. This data is made available by NLCD for 2001, 2006, and 2011. It would also be interesting to consider the temperature change associated with specific land cover transitions, including those more extreme transitions, such as areas that went from densely forested to intensely urbanized, or more natural progressions from shrubs/scrub to evergreen forests. In this way, mitigation efforts, such as protected areas, reforestation, green roofs, etc. may be evaluated. This temperature change surface could also be used to justify the importance of parks and other non-urbanized areas.

Concluding Remarks

Central Texas experienced exceptional effects of "The Great Drought of 2011." Not only has this strained water supply and increased energy consumption (Combs 2012), but it has also resulted in the loss of more than 100 million trees (6.6%) in Central Texas (Texas A&M Forest Service 2012). In fact, the entire state of Texas lost an estimated 5.6 million shade trees in urban areas due to the drought – a number that is expected to rise (Texas A&M Forest Service 2012). Investigations regarding the spatial patterns of urban "hotspots" or increases in land surface temperature change over time can provide important information for a heat-stressed state.

Acknowledgements

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Tables

Table 1. Summary statistics of entire study area land surface temperature change over time

Min	-2.3
Max	9.0
Mean	2.4
Std dev	2.0

Table 2. NLCD land cover types in Travis County in 2001 and 2011; change in land cover types from 2001 to 2011.

Value	Land Cover Type	% Cover		Change in
		2001	2011	land cover
42	Evergreen Forest	22.0%	20.3%	-1.7%
52	Shrub/Scrub	16.8%	15.6%	-1.2%
21	Developed, Open Space	12.4%	12.0%	-0.4%
71	Herbaceuous	11.2%	10.6%	-0.6%
41	Deciduous Forest	8.6%	7.7%	-0.9%
22	Developed, Low Intensity	6.5%	7.7%	1.2%
82	Cultivated Crops	6.3%	6.7%	0.4%
23	Developed, Medium Intensity	4.1%	6.4%	2.3%
81	Hay/Pasture	4.1%	4.2%	0.0%
11	Open Water	3.3%	3.3%	0.0%
24	Developed, High Intensity	2.0%	2.7%	0.6%
90	Woody Wetlands	1.8%	1.8%	-0.1%
43	Mixed Forest	0.6%	0.6%	0.0%
31	Barren Land	0.1%	0.4%	0.3%

Table 3. Percent of temperature change explained by change in developed and agricultural land between 2001 and 2011

	Cover Type Changes (pixels)		
Temperature Increase (C)	Developed	Agricultural	Study Area
6 - 7	4267	30701	109019
7 - 8	1084	9664	36165
8 - 9	354	3386	13508
Total	**5705**	**43751**	**158692**
% explained	4%	28%	
Total	**31%**		

Figures

Figure 1. Study area highlighted in red (Travis County, Texas). Projection: WGS 1984 Web Mercator Auxiliary Sphere

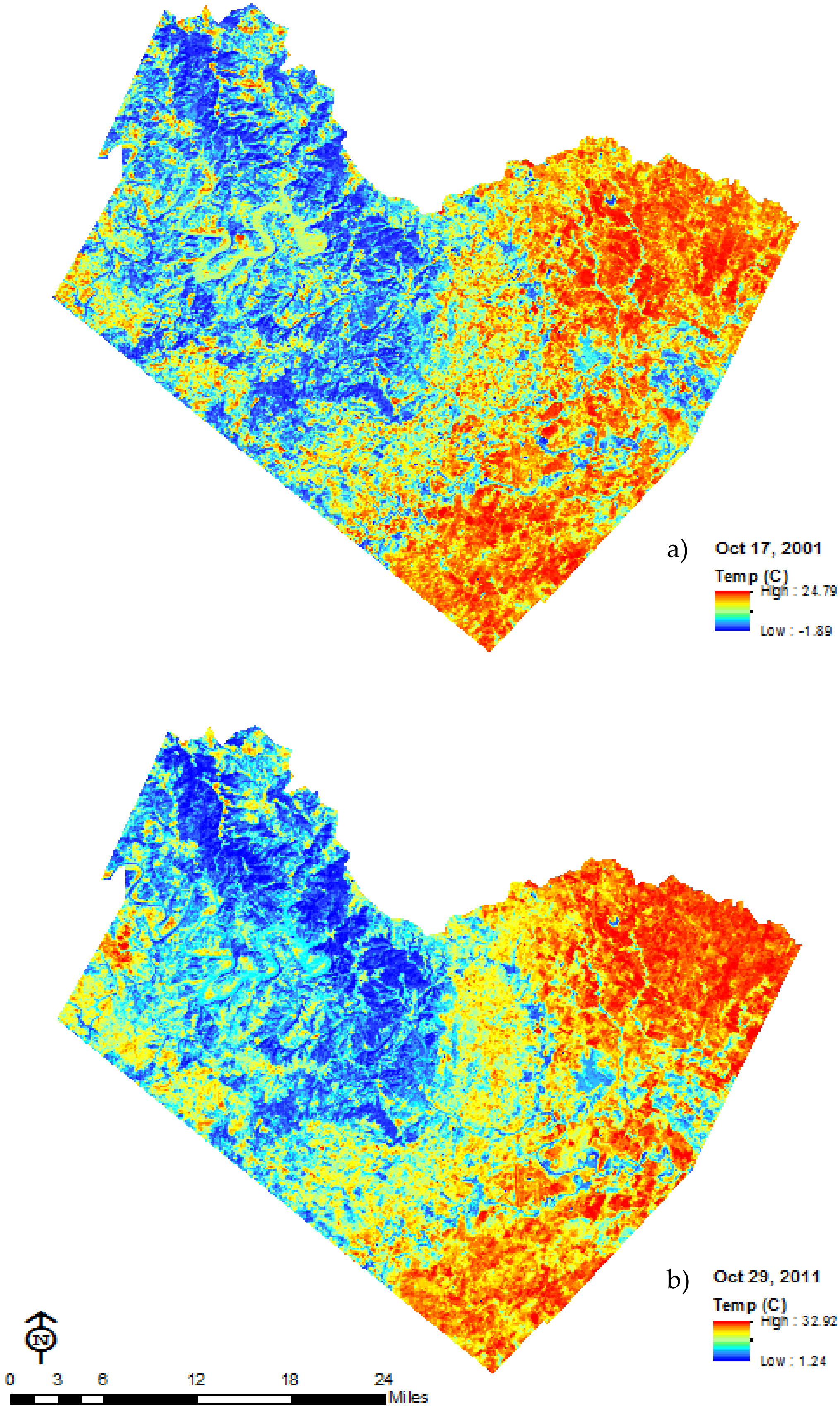


Figure 2. Landsat TM band 6 CDR images with histogram equalize stretch

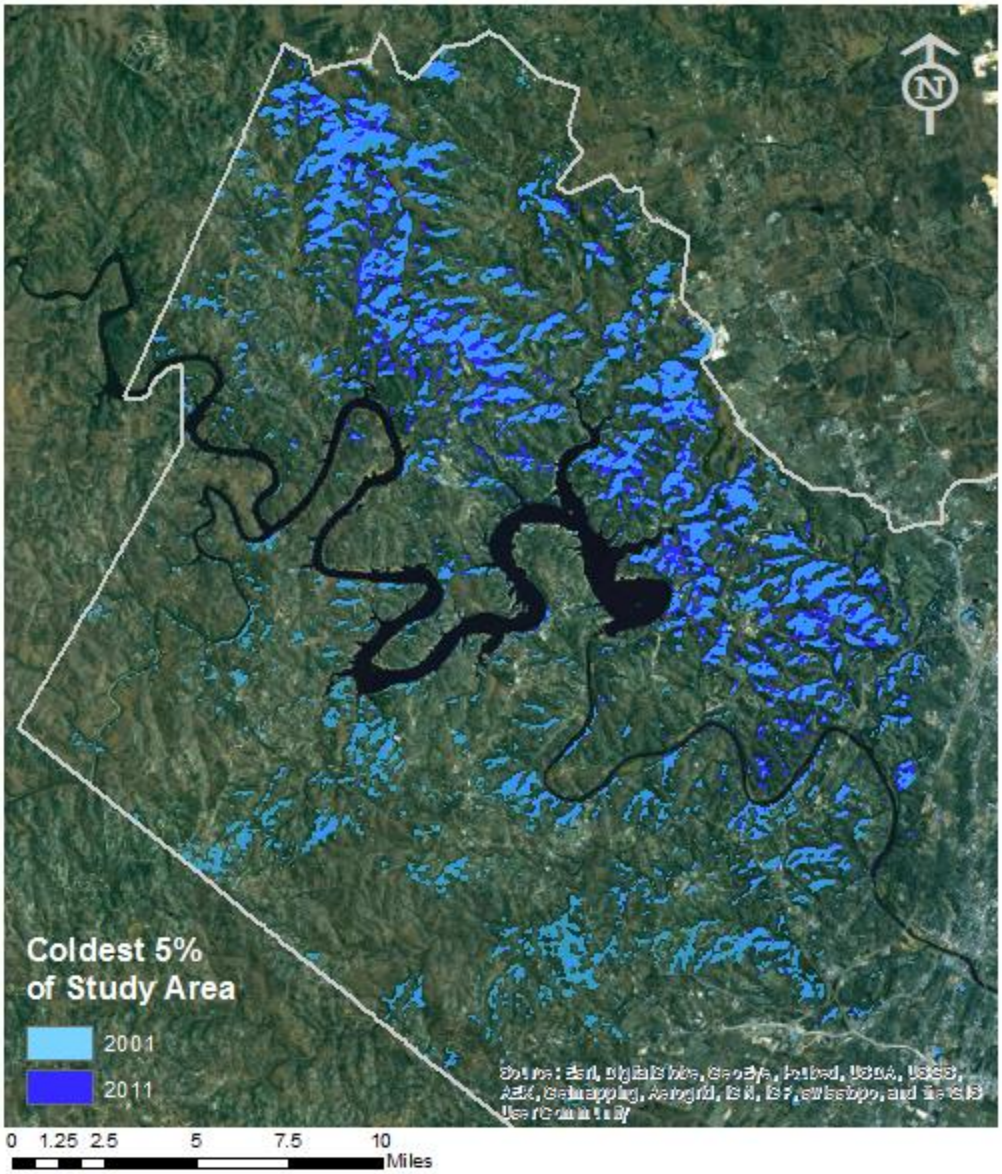


Figure 3. Eastern Travis County pixels with the 5% coldest temperatures on Oct 17, 2001 and Oct 29, 2011

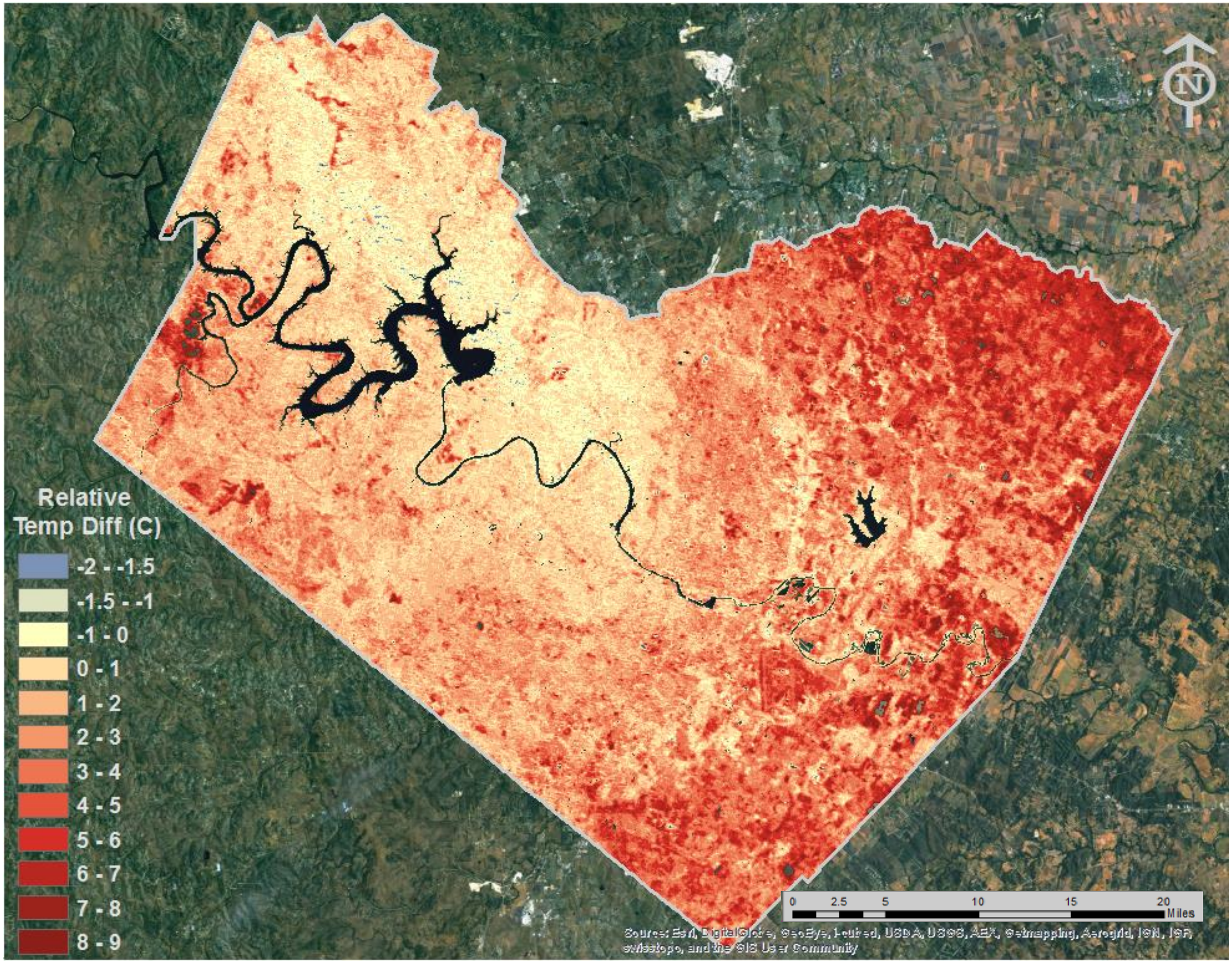


Figure 4. Temperature difference (relative to coldest 5% of pixels) in Travis County between 2001 and 2011. Outlying pixels were removed (-10.33 - -2.23; 9 – 14.33)

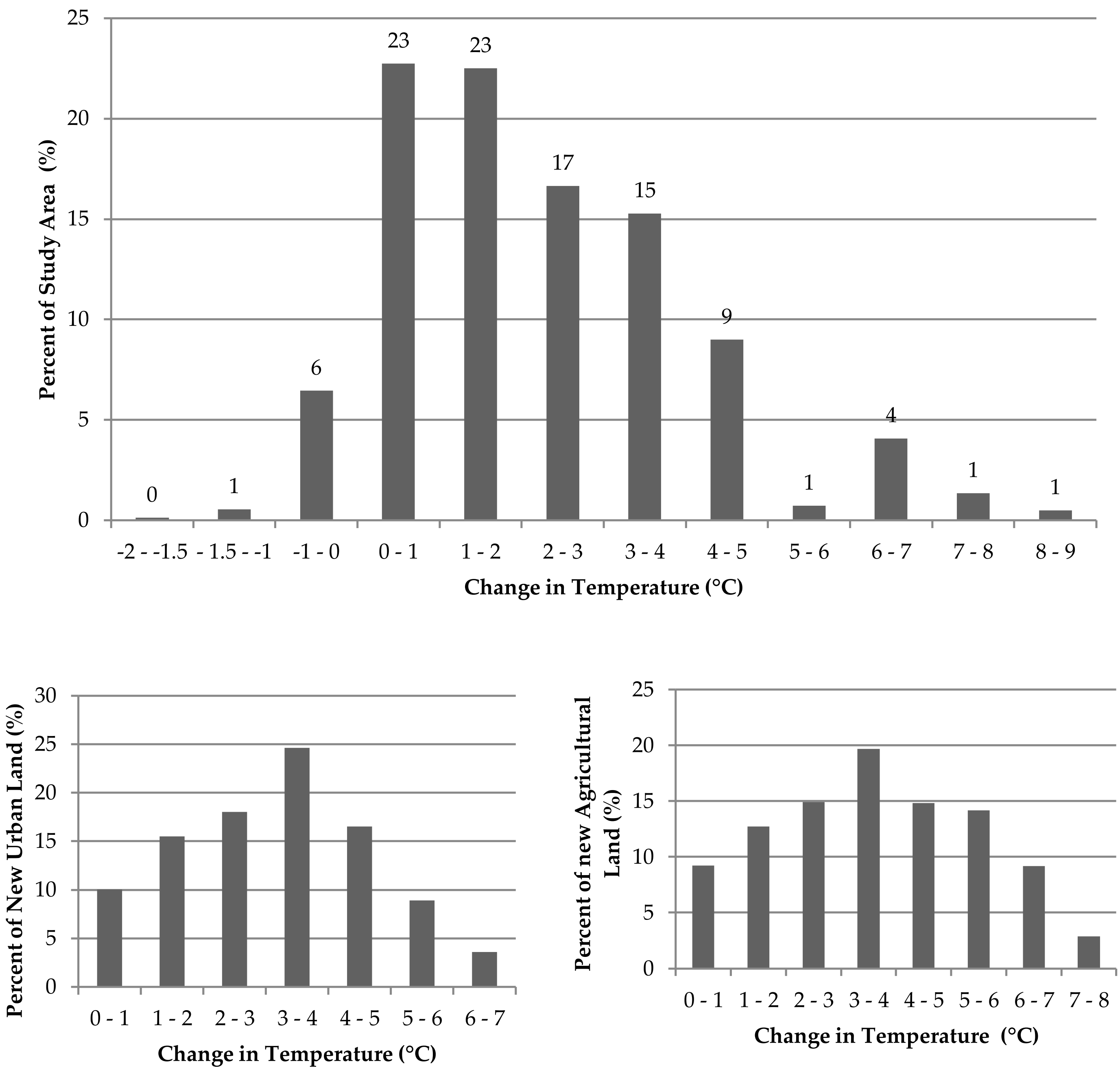


Figure 5. a) Percent of study area vs change in temperature (mean = 2.43°C); b) Percent new urban land vs change in temperature (mean = 3.28°C); c) percent new agricultural land vs change in temperature (mean

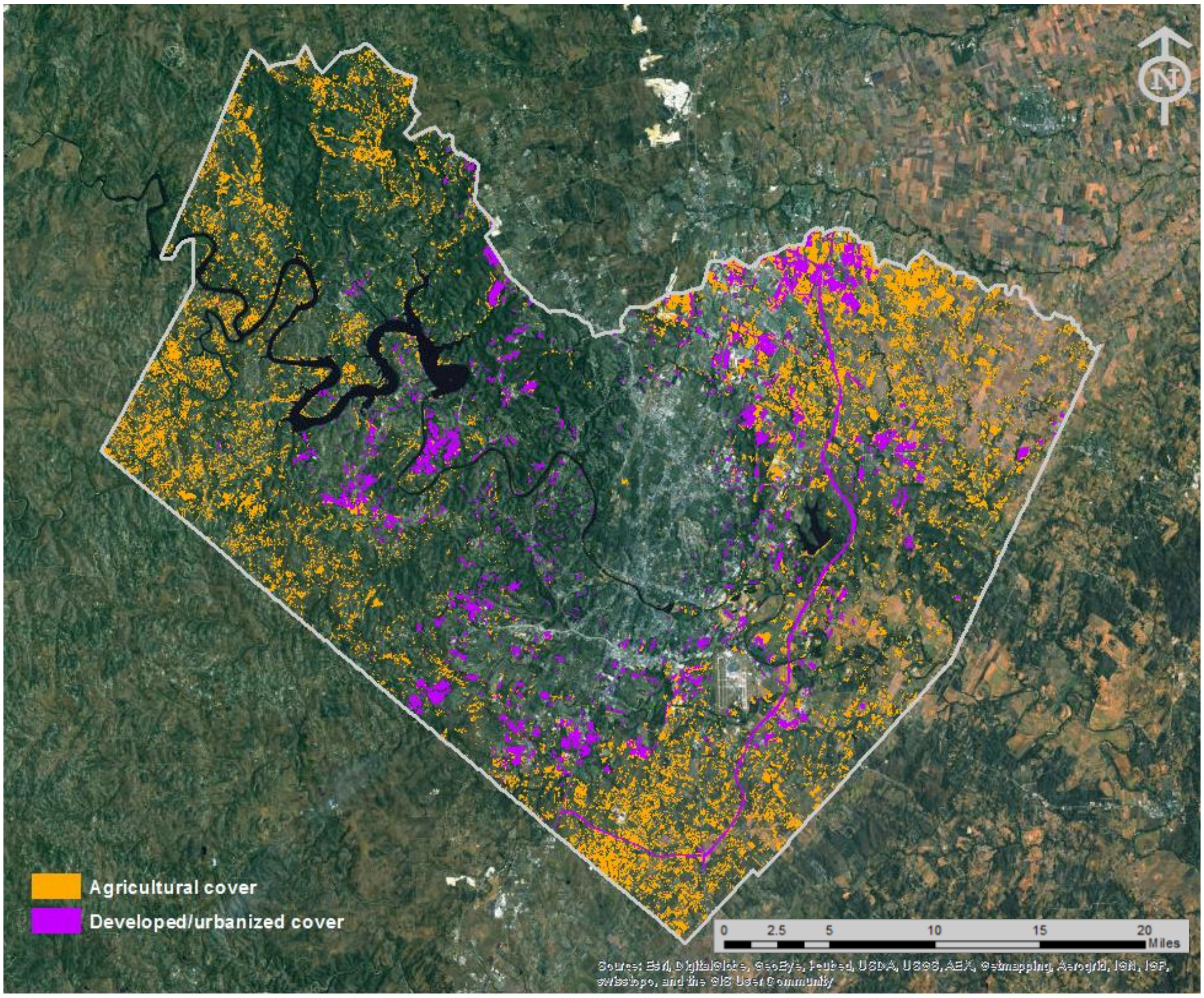


Figure 6. "New" agricultural and developed/urbanized cover in 2011 (since 2001)

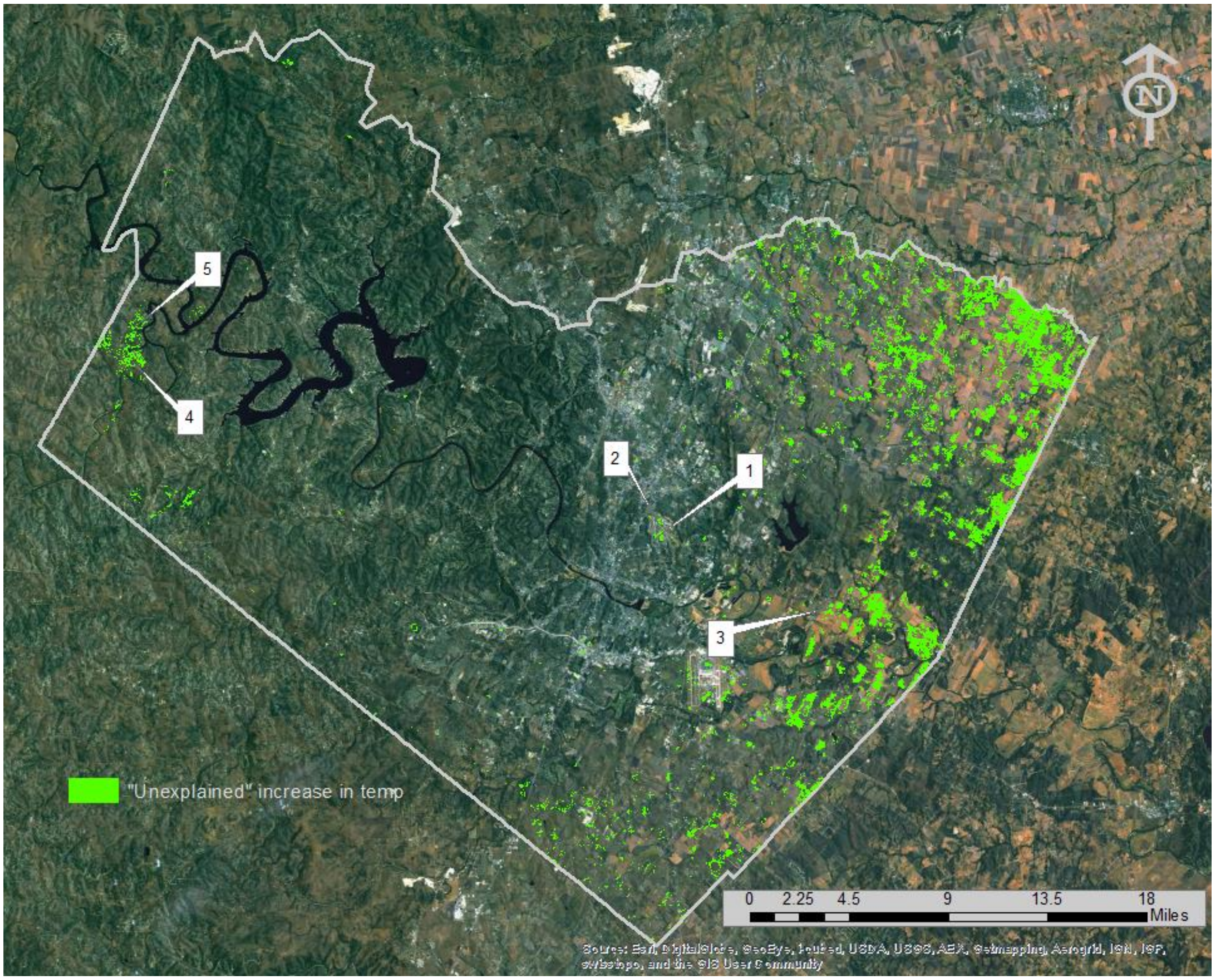


Figure 7a. Areas of high increase in temp (6 – 9 C) unexplained by change in urban or agricultural land cover increase

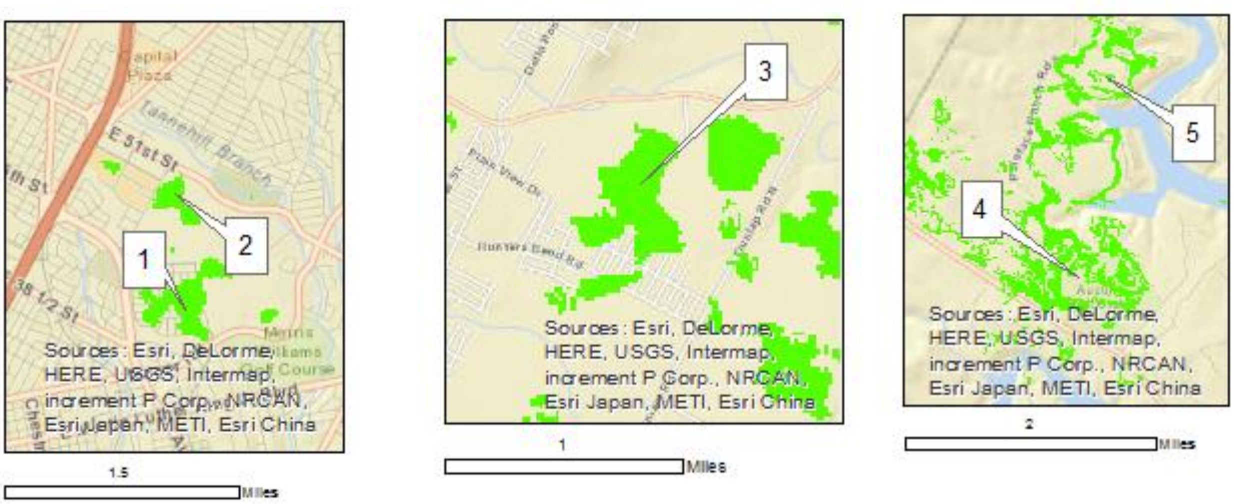
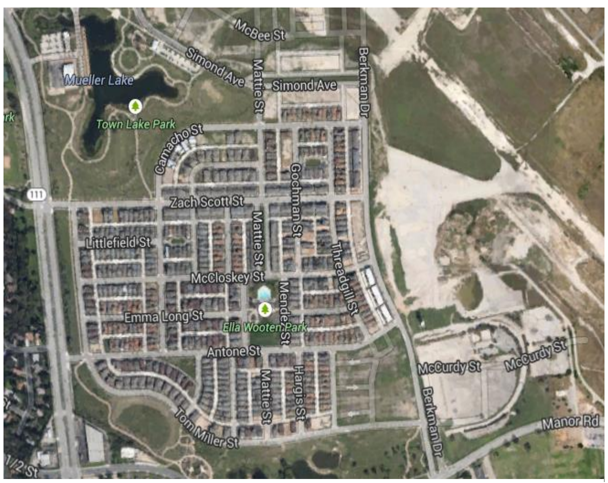


Figure 7b. The locations indicated in the figure above are areas where development most likely occurred after classification of the 2011 NLCD but before the satellite image was taken.

Site 2, construction north of the Mosaic at Mueler Apartments

Site 5: New development north of the Omni Golf Course



Site 1: Mosaic at Mueler Apartments

Site 4: Omni at Barton Creek Resort & Spa Golf Course

Site 3: Farm to market center

Figure 7c. Support for this assumption (see Figure 7b caption) is provided by Google Maps satellite images.

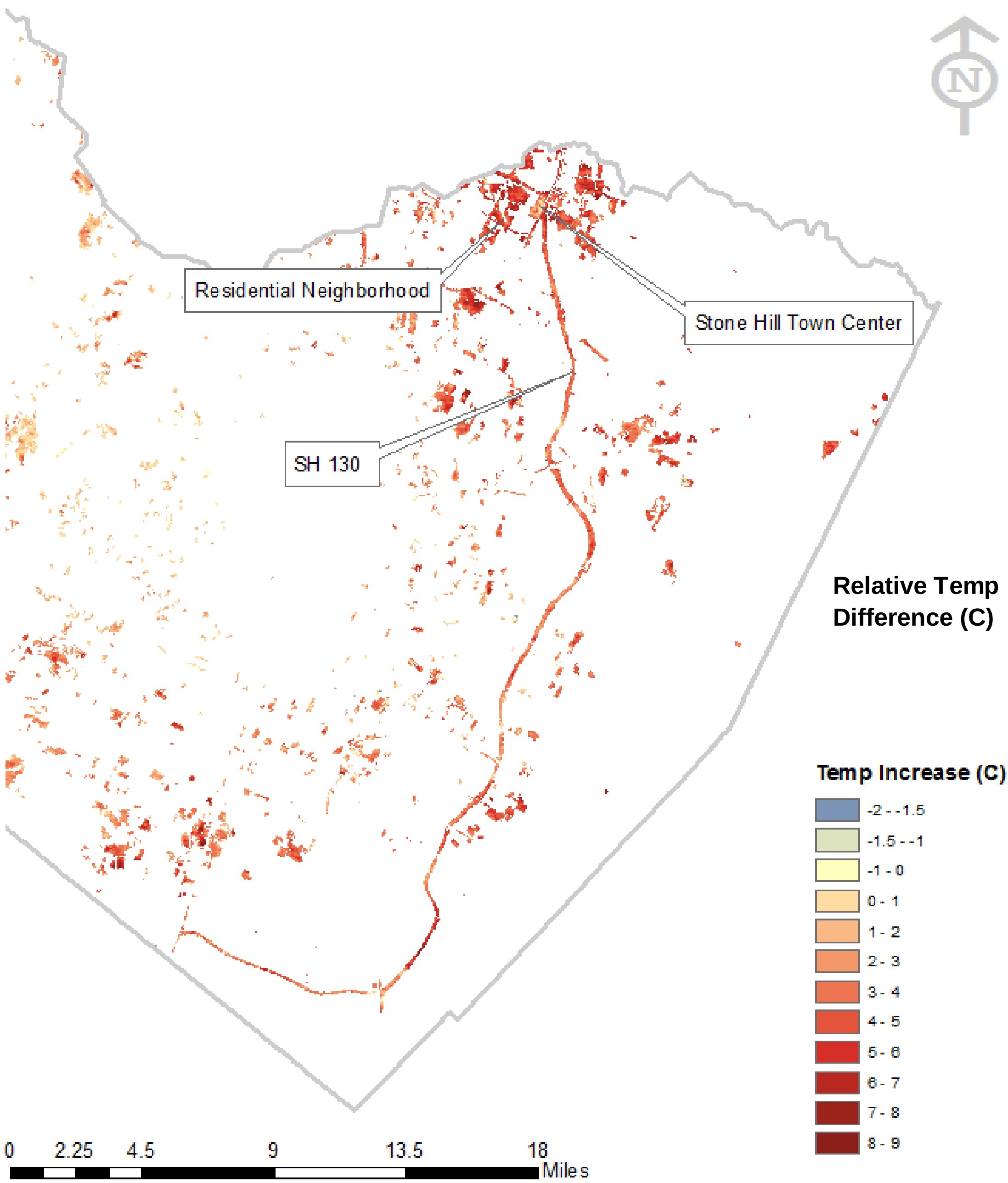
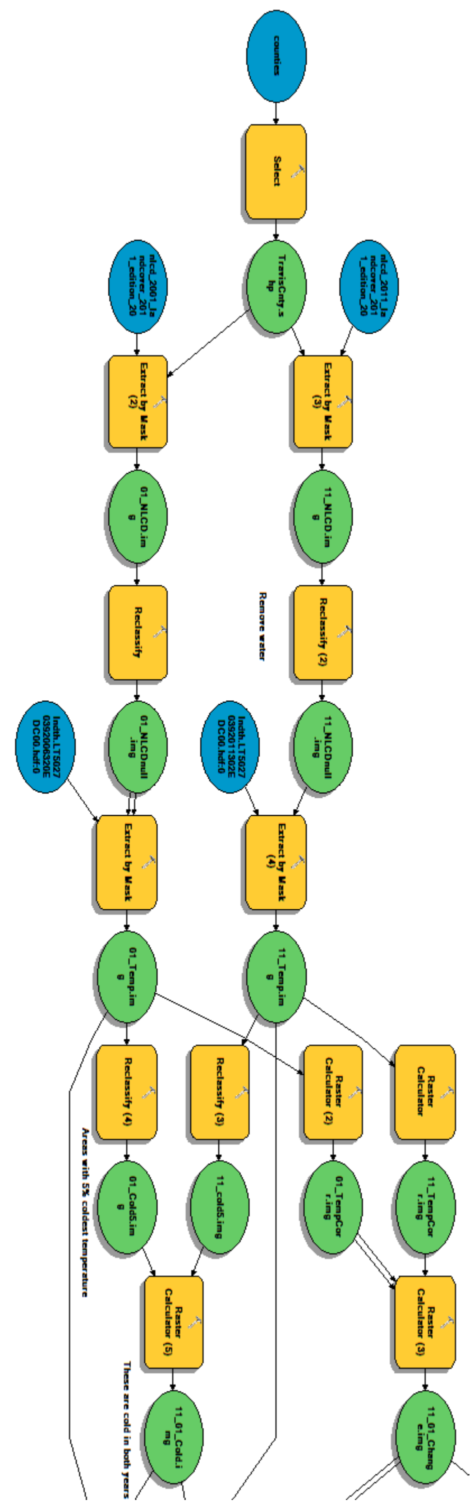


Figure 8. Relative temperature difference of "new" developed areas in east Travis County

Models

1)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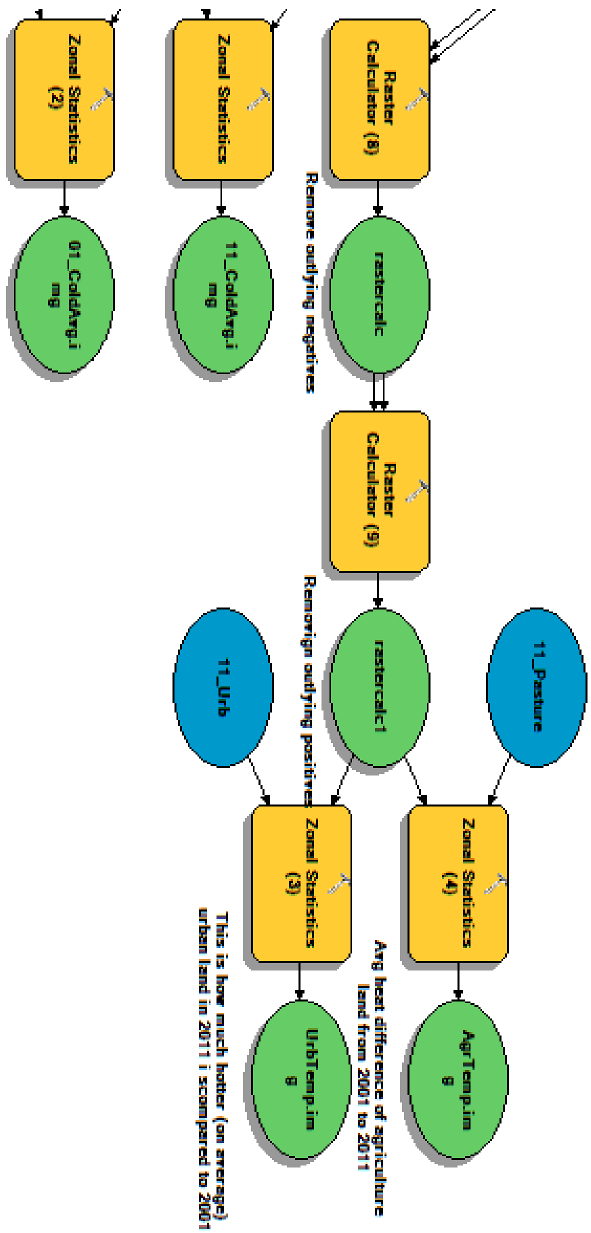
Raster Calculator
Raster Calculator (2)
Reclassify (3)
Reclassify (4)
Raster Calculator (3)
Raster Calculator (5)
Areas with 5% coldest temperature
These are cold in both years

2)


Raster Calculator (8)
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Remove outlying negatives
Raster Calculator (9)
rastercalc1
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Zonal Statistics
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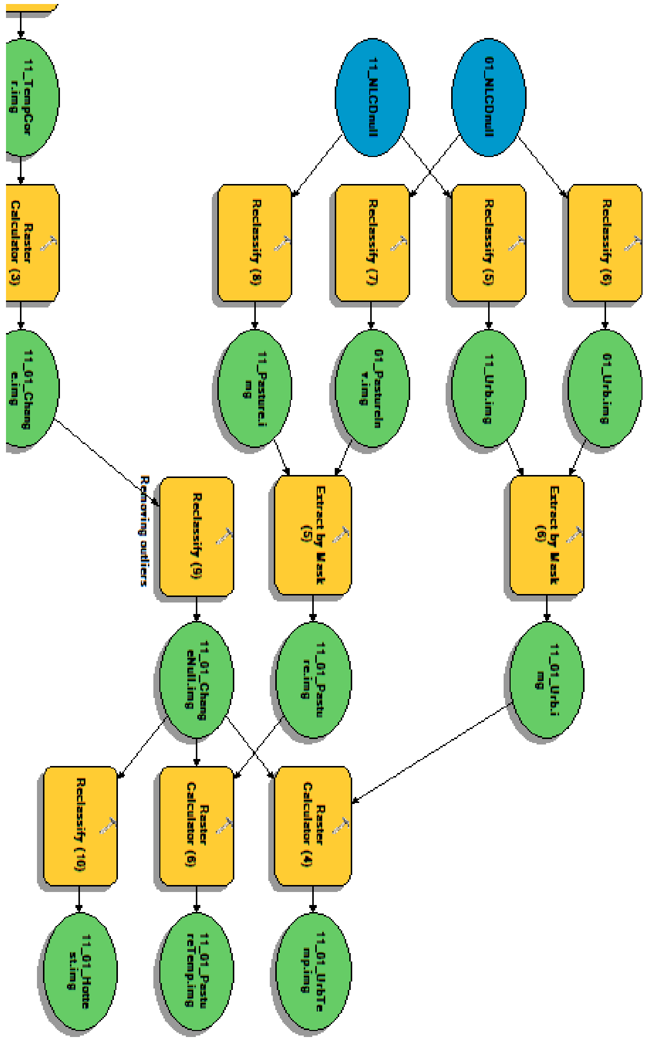
Zonal Statistics (2)
01_ColdAvg.img
11_Pasture
11_Urb
Zonal Statistics (4)
Zonal Statistics (3)
AgrTemp.img
UrbTemp.img
Avg heat difference of agriculture land from 2001 to 2011
This is how much hotter (on average) urban land in 2011 i scompared to 2001

3)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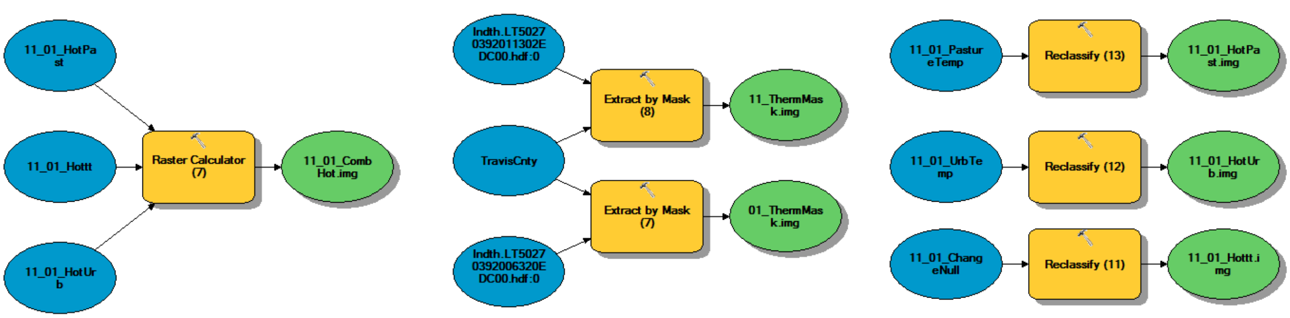
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