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ASSESSING THE INFLUENCE OF WEATHER TYPE AND RURAL LAND COVER ON A SMALL URBAN HEAT ISLAND

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ABSTRACT: *Temperature data were collected for a year from a set of rural and urban stations around the borough of Shippensburg, Pennsylvania, USA, with the goal of examining the urban heat island (UHI) associated with a smaller urban area. Additionally, the impacts of seasonality, variable weather, rural station location, and land use change on the UHI magnitude were analyzed. On average, the UHI ranged from 0.6°C in the winter to 1.2°C in the summer with an annual average of 0.9°C. The UHI is maximized between the hours of 1800 to 0400 LST in winter, and 2000 to 0200 LST in spring, summer, and fall. A smaller daytime urban cool island existed in every season except winter during the late morning hours. For all seasons, the largest UHIs were prevalent during dry polar and dry moderate weather types. The largest of these UHIs occurred during warm, dry, calm, and high pressure conditions. Differences existed between collocated rural sites with different land cover types implying that rural location choice will influence the UHI calculation. Applying the collocated temperature values to a land use land cover classification indicated that the UHI may increase by as much as 1.0°C in the extreme case of complete conversion of rural land cover types to urban. Conversion of rural agriculture and grassland to forest results in up to a 0.2°C decrease in the UHI.*

Key Words: *urban climatology, weather type, land use land cover, Pennsylvania, United States*

INTRODUCTION

By 2030, about 60% of the world's population is projected to live in urban areas (PRB, 2007). Consequently, the impact of population growth and development on urban climate, and the urban heat island (UHI) specifically, has been well studied and documented. The majority of UHI studies have focused on the UHIs of large cities such as New York City (Holt and Pullen, 2007), London (Meyer, 1991), Phoenix (Hawkins et al., 2004) or Melbourne (Coutts et al,. 2007). Little attention has been paid to the development of UHIs associated with smaller urban areas or on the role that rural landscapes play in measuring the UHI. In many locations, these smaller urban areas are developing rapidly, and thus it is important to document the magnitude and extent of any existing UHI so the information may be used as a baseline to assess the impact of future growth. Additionally, many smaller urban areas exist in a landscape that would otherwise be characterized as rural. This stands in contrast to most UHI studies where the urban footprint is so large that it is often difficult to establish the boundary between urban and rural and the rural landscape used as a control may in fact be better classified as suburban. Finally, as noted in Stewart (2011), controlling for the influence of weather and seasonality is a critical component of UHI assessment. This study seeks to address these issues by examining a small urban area in south central Pennsylvania, USA that is surrounded primarily by an agricultural landscape. The goals of the study were to enhance the literature regarding UHIs associated with smaller urban areas, highlight the importance of selecting rural locations as controls, assess the influence on the UHI of future growth to a small urban area, and assess the impact of seasonality and variable weather on UHI magnitude.

The causes of UHI formation are well studied and documented. Oke (1982), Arnfield (2003) Voogt (2004), Chapman (2005), Souch and Grimmond (2006), and Roth (2007) have all reviewed and synthesized this literature. The following is a very brief synopsis of their work regarding the many factors that contribute to UHI formation. The UHI is based on heat energy gains and losses. Roads, buildings, and other urban infrastructure absorb solar radiation, store it more effectively as heat, and release that heat more slowly than rural surfaces. Taller buildings in urban environments produce multiple reflections of solar radiation which ultimately leads to greater overall radiation absorption. By increasing the roughness length and therefore friction, tall buildings also decrease wind-aided cooling. Urban structures generally do not allow for water infiltration and therefore water that would normally be available for evaporative cooling through soil moisture or plant transpiration is quickly moved out of the urban environment via intricate stormwater management systems. Finally, industry, motor vehicles, and other human activities contribute anthropogenic waste heat. These same activities often also release pollutants that form a "blanket" over urban areas and increase local greenhouse warming by absorbing outgoing terrestrial radiation and reemitting it to the surface.

Of specific relevance to this study are the impacts of seasonality, weather, and rural land use on the UHI in smaller urban areas. UHIs typically are strongest during the nighttime hours (Oke, 1982; Runnalls and Oke, 2000). An urban cool island effect is often observed in the mid-morning hours when shading from buildings serves to keep the urban area cooler than the rural area. From a seasonal standpoint, the largest UHI for a location typically occurs during the driest and least windy season. For many locations these conditions are achieved during summer (Roth, 2007). Large UHIs also are often associated with high sea level pressure conditions (Morris and Simmonds, 2000) which often produce calm and dry conditions.

The magnitude of the UHI can be enhanced due to the conversion of agricultural land to residential, industrial, or commercial land uses (He et al., 2007; Hu and Jia, 2010). This idea is especially relevant when considering small urban areas that are primarily surrounded by agricultural land. For these smaller urban areas it is also important to consider the role that various rural land cover types or locations may have on the UHI magnitude as this issue has been shown to be influential (Hawkins et al., 2004; Sakakibara and Owa, 2005).

STUDY AREA

The borough of Shippensburg is located in south-central Pennsylvania, USA and is surrounded by Southampton, Lurgan, and Hopewell Townships (Figure 1). The approximate elevation for the area is 200 m above sea level. The urban population and population density are 10,921 people and 1365 people/km^2 respectively (U.S. Census Bureau, 2010). The surrounding rural population and population density are 19,344 people and 49 people/km^2 respectively (U.S. Census Bureau, 2010).

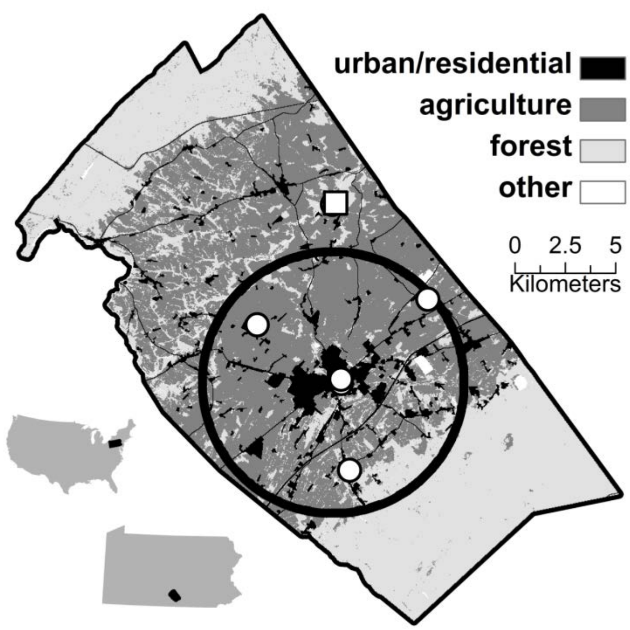

Figure 1. Study area. The boundary of the main map represents the local municipal boundaries. Subdivisions of the municipality boundaries within the map are not shown. White circles represent stations that were used in the overall UHI analysis. The white square represents the location of the three collocated stations that were used in the land use impact part of the analysis. The black circle around the urban center represents the 6.5 km radius area used in the analysis.

Shippensburg's land use mainly consists of areas of high and low urban density while the surrounding townships are mostly agricultural and pasture lands with smaller amounts of forest (Figure 1). The largest buildings in the urban core are three stories high and the urban "canyons" have an approximate height to width ratio of 1-2. In the surrounding areas, the primary crops grown are corn and soybeans. The transition zone between forest and agriculture also represents the edge of the valley floor where elevations begin to increase.

The Köppen climate classification for Shippensburg is humid continental. The average annual daily temperature, as recorded by the National Weather Service/National Climatic Data Center's Cooperative Observers Network station at Shippensburg University, is 12°C, with an average annual high of 17°C, and an average low of 6°C (Shippensburg University, 2011). A pilot study was conducted during the summer of 2007 to initially assess the UHI and indicated a 0.8°C to 1.9°C summertime UHI value (Doyle and Hawkins, 2008).

DATA AND METHODS

Temperature data were collected from eight locations around the Shippensburg area (Figure 1) from December 1, 2008 through November 30, 2009 using HOBO Pro T/RH sensors contained in naturally ventilated radiation shields 2 m above the surface. Temperature values had a standard deviation of ± 0.2°C. Two of the stations were located near the borough center and were considered urban while three stations surrounded the borough and were considered rural. These two sets of stations were averaged to create urban and rural time series. Additionally, three rural stations were collocated on a property outside of Shippensburg. These three stations were in approximately the same location but had different land cover types and could therefore be used to assess the impact of land cover on the UHI. Table 1 lists the characteristics of all stations. Elevation differences between the stations were minimal.

Hourly data were collected at each station and were used to calculate seasonal averages for daily and hourly time scales. Seasons were defined as: winter = DJF, spring = MAM, summer = JJA, and fall = SON. Day was defined as 0800 through 1900 LST and night was defined as 2000 through 0700 LST. Urban and rural averages, as well as the differences between the urban and rural averages (U-R), were calculated for the same time scales based on the stations described previously. Missing data were minimal with a few exceptions as listed in Table 1. Significant missing data were due to battery failure and vandalism. To be consistent and to account for missing data, the spring season began on March 6. Additionally, for analyses using the collocated rural stations, the winter season was not examined due to significant missing data for some of these stations.

To assess the impact of weather conditions on the UHI, daily weather type data were obtained for Harrisburg airport from the Spatial Synoptic Classification data set (SSC) (Kalkstein et al., 1996; Sheridan, 2002) available from Kent State University (http://sheridan.geog.kent.edu/ssc.html). Harrisburg is approximately 60 km from Shippensburg and is the nearest station with SSC data. The SSC uses surface meteorological conditions to develop seed days for each weather type for each season. Seed days are days that are meteorologically most representative of each weather type. Actual meteorological conditions are then compared to the seed day conditions to determine the weather type for each day at a given location. The weather types are dry polar (DP), dry moderate (DM), dry tropical (DT), moist polar (MP), moist moderate (MM), moist tropical (MT), and transition (TR). For each season and for each weather type, the average nighttime and daytime U-R value was calculated.

Table 1. Characteristics of the stations used in the study.

Site	Classification	Land Use	Missing Data
1	urban	high urban density	none
2	urban	high urban density	none
3	rural	maintained grass; medium density residential	none
4	rural	maintained grass; low density residential	Dec. 7, 1500 to Dec 10, 1500
5	rural	maintained grass; low density residential	none
6	collocated rural	field corn	Dec. 7, 1300 to Jan. 4, 1100
7	collocated rural	mature deciduous forest	none
8	collocated rural	maintained grass	Jan 4, 1300 to Mar. 5, 1400

In addition to examining U-R values in total, the days with the ten largest and smallest nighttime and daytime average U-R values were selected for further analyses. Local air temperature, dew point temperature, wind speed, and pressure recorded with a Davis Vantage Pro2 weather station, collocated with the Shippensburg National Weather Service/National Climatic Data Center cooperative observer network station, were averaged for these sets of days. The prevalence of each SSC weather type was also totaled for these days. Finally, composite sea level pressure maps were created for the extreme U-R days using data from the National Center for Environmental Prediction/National Center for Atmospheric Research reanalysis dataset (Kalnay et al., 1996) which is served by the National Oceanic and Atmospheric Administration's Earth System Research Laboratory (http://www.esrl.noaa.gov/psd/data/composites/day/).

To assess the influence of land use- land cover (LULC) and changing agricultural conditions on U-R values, differences were calculated between the average nighttime urban temperature (stations 1-2 in Table 1) and each of the collocated rural stations (stations 6-8 in Table 1) individually to determine a UHI value for each land cover type. Differences between these three UHI values were then calculated on a daily basis and a 10-day average was applied to the time series to smooth the data. The time series of the UHI differences were further separated based on SSC weather type as large changes in UHI values were evident based on weather type.

Average seasonal nighttime temperature for each of the three collocated rural land cover types were calculated and used to assess the impact of potential LULC change on the UHI. Due to missing data, this analysis was not performed for winter. A 6.5 km radius circle was established around the center point of the urban core (Figure 1) and used as the study area for this component of the analysis. The ratio of urban, agriculture, grass, and forest LULC types was established within the circle. Rural temperature was calculated as the weighted average of the three rural temperatures, as determined by the collocated rural stations and the ratio of each rural land cover type within the study circle. Urban temperature was simply calculated as the seasonal urban average as used in previous analyses. The UHI was calculated as the difference between urban and rural temperatures. This methodology assumes that the measured urban and collocated rural temperatures can be applied to every pixel in the LULC data circle. While this assumption is likely not completely true, it does allow for a more global UHI calculation and provides a methodology for future studies to build upon.

When LULC change scenarios contained only a change within the rural land cover types, the weighted rural average was simply recalculated using the new land cover ratios. When rural land cover types were converted to urban land use, the increase in temperature was first calculated for the entire circle. This increase in temperature was added to the current baseline urban temperature to determine the new urban temperature. Rural temperature was still calculated as a weighted average. In the extreme case where the entire circle was converted to urban land use, urban temperature was calculated in the manner just described while rural temperature was assumed to be the current baseline rural temperature.

RESULTS AND DISCUSSION

Figure 2 shows the average seasonal hourly urban and rural temperatures as well as the U-R values, while Figure 3 shows the daily nighttime U-R value. The UHI shows an annual cycle with largest values in the summer and smallest values in the winter. Over the course of a full 24-hour day and for all seasons, the U-R value is consistently 0.5 or 0.6°C. The error associated with the instruments is ± 0.2°C . At night however, when the UHI typically manifests itself, U-R ranges from 0.6°C in the winter to 1.2°C in the summer with an annual average of 0.9°C. The magnitude of the nighttime UHI is largest in summer but is also relatively short beginning on average at 1800 and ending at 0700. The winter, spring and fall UHI ends between 0800 and 1000. The temporal timing of the beginning of the UHI is not nearly as pronounced during the winter, spring, and fall compared to the summer. The largest nighttime UHI value was 3.3°C on July 8 and the largest single hour UHI value was 5.8°C at 0200 LST on that same day.

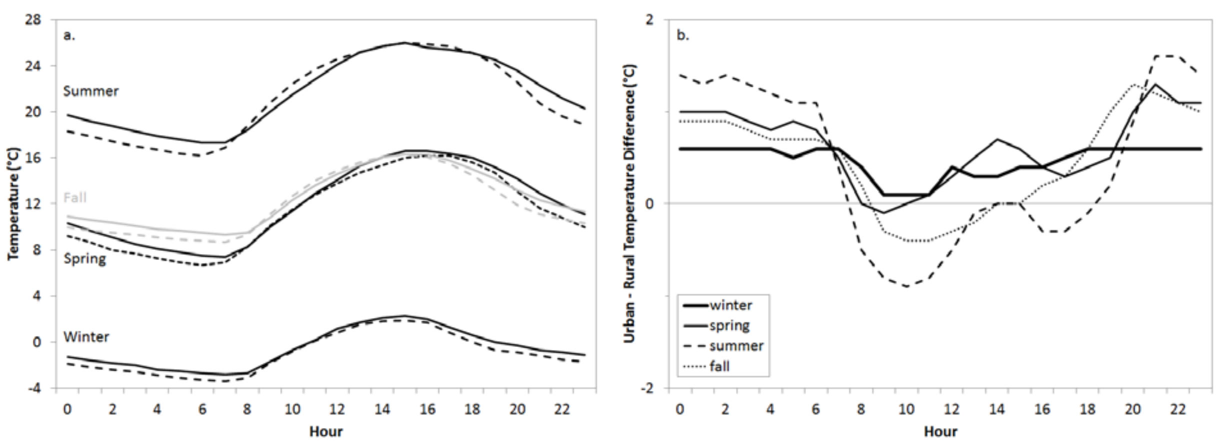

Figure 2. Average seasonal hourly urban and rural temperatures (a) and temperature differences (b). For (a), solid lines are urban temperature and dashed lines are rural temperature.

During the day, U-R is consistently smaller compared to the night and when averaged over the year is 0.0°C. During the summer, there is actually an urban cool island effect where the urban stations are 0.3°C cooler than the rural stations when averaged over the daytime hours. The urban cool island actually exists for selected hours on average for all seasons except winter (Figure 2b). All seasons do exhibit a decrease in U-R during the day. The duration of the cool island is longest during summer and hence the average negative U-R day value.

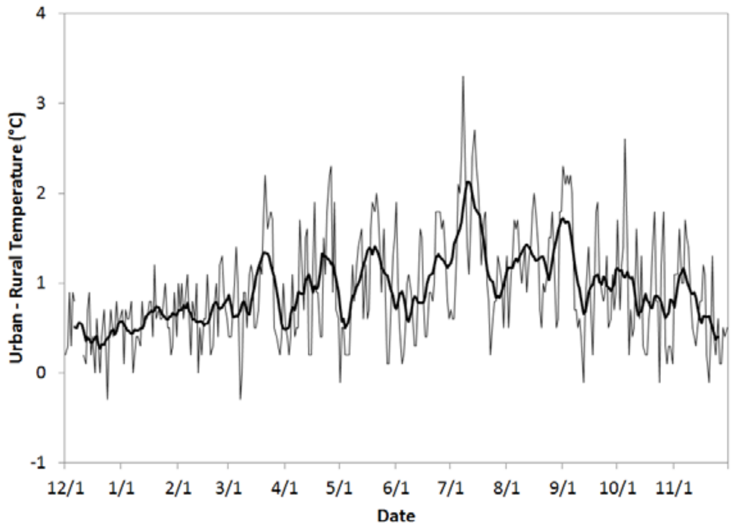

Figure 3. Daily nighttime urban – rural temperature difference.

Figure 4 shows the average night and day U-R value for each season and for each weather type. Also shown are the number of days that each weather type occurred. Nighttime UHI U-R values are largest in all seasons during DP followed by DM conditions. For spring, DP, DM, and DT differences are actually all tied for being the largest. There were too few DT days in winter, summer and fall to be considered. While the actual conditions differ between seasons, the DP and DM weather types are characterized as cool/cold and dry and are often associated with stable air masses that have migrated from Canada behind a cold front. Nighttime UHI values are smaller in all seasons for all the moist weather types although no pattern between seasons exists between the three moist weather types.

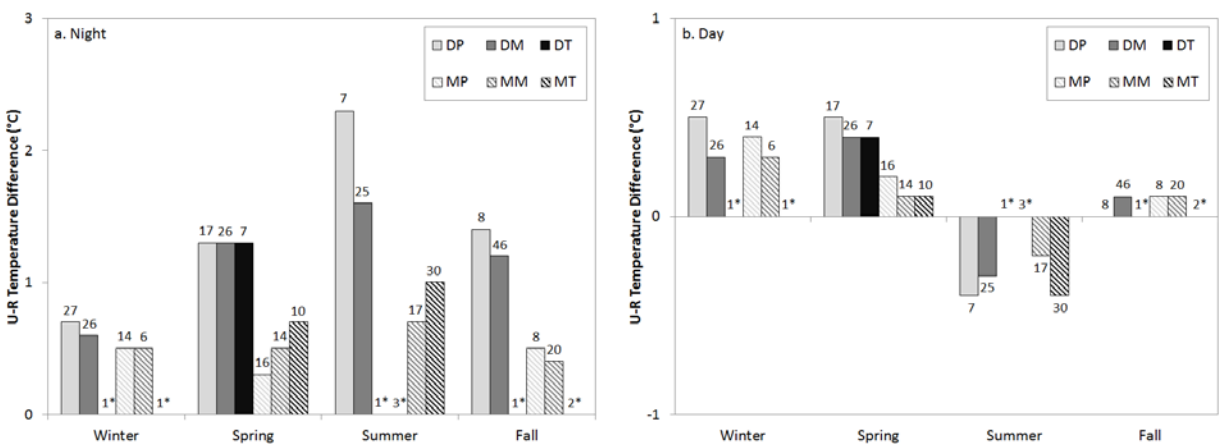

Figure 4. Average seasonal night (a) and day (b) urban-rural temperature differences for each weather type. DP = dry polar; DM = dry moderate; DT = dry tropical; MP = moist polar; MM = moist moderate; MT = moist tropical. The number associated with each bar represents the number of times the particular weather type occurred during the season. Numbers with a * indicate that the number of days was too small to be considered and the difference bar has been removed from the chart.

As discussed previously, daytime U-R values are smaller than nighttime values when considered by weather type. Daytime winter and spring U-R values have a similar pattern as nighttime values in that the drier and colder weather types produce the larger differences. In winter, the differences between weather types are small. During summer, an urban cool island exists for all weather types with the largest values occurring under DP and MT conditions. These weather types are both generally characterized by stable air masses although their source regions differ with DP coming from central Canada and MT coming from the Gulf of Mexico or Atlantic Ocean. Fall shows very small and nearly equal U-R values for all weather types.

Table 2 shows actual and expected occurrence of SSC weather types for the ten largest and smallest nighttime and daytime U-R values. Shaded values indicate that the largest nighttime UHI values occurred under DP, DM, and DT conditions for all seasons while the smallest nighttime UHIs were observed under MP, MM, MT, and TR conditions. The pattern is not as clear when considering the largest daytime cool island when urban temperatures are cooler than rural temperatures. Generally however, the largest cool island occurred during dry weather types. This is especially true during spring and fall. During summer, the largest oases actually occurred mostly during moist weather types, especially MM. Clear patterns do not exist for the smallest day cool island (also known as the largest day UHI) because day is not the optimum time for UHI formation.

Table 2. Number of days for a given weather type associated with the ten largest and smallest urban heat island and cool island values. Also shown in the last set of rows as the expected occurrence is the number of days (out of ten) that a given weather type occurred during the study. Shaded values indicate counts that exceeded the expected number by at least 0.9 days.

		Dry Polar	Dry Moderate	Dry Tropical	Moist Polar	Moist Moderate	Moist Tropical	Transition
Largest Night UHI	Win	4	3		2			1
	Spr	3	4	3				
	Sum	5	5					
	Fal	2	8					
Smallest Night UHI	Win		3		3	1		3
	Spr			1	2	3	2	2
	Sum				3	5	2	
	Fal		2		2	5		1
Largest Day Cool island	Win	5	1		3			1
	Spr	3	4	3				
	Sum		2		1	5	2	
	Fal	1	9					
Smallest Day Cool island	Win		3		1	1	1	4
	Spr	1	3	2		2	2	
	Sum	1	4				5	
	Fal	1	9					
Expected Occurrence	Win	3.1	3.0	0.1	1.6	0.7	0.1	1.3
	Spr	1.9	2.8	0.8	0.7	1.6	1.1	1.2
	Sum	0.8	3.0	0.1	0.3	2.0	3.4	0.3
	Fal	0.9	5.1	0.1	0.9	2.2	0.2	0.6

Table 3 shows the prevailing weather conditions during these same days. With a few exceptions, large nighttime UHIs and daytime oases are associated with warmer, calmer, and higher sea level pressure conditions. These conditions are consistent with large high pressure systems that allow for rapid rural nighttime cooling due to lack of cloud cover and little mixing of urban and rural conditions due to low wind speeds. Interestingly, large nighttime UHI values are characterized by drier conditions while large daytime cool island values are characterized by more humid conditions. Drier conditions promote larger UHI development by allowing terrestrial radiation to escape more rapidly and thus maximizing the difference between urban and rural environments.

Figure 5 shows seasonal composite sea level pressure fields for the largest and smallest UHI days. Large UHIs are characterized by high pressure systems that are established over the eastern U.S. and the accompanying weak pressure gradient. In the spring, summer, and fall, these pressure systems extend into the Atlantic, while in the winter the high is focused primarily over the land surface. Small UHIs are characterized by low pressure centers overhead in winter, summer, and fall and a strong pressure gradient in spring due to low pressure to the west and high pressure to the east. These pressure patterns are consistent with the weather type and meteorological data discussed previously.

Table 3. Average urban-rural temperature differences and meteorological conditions associated with the ten largest and smallest urban heat island and cool island values. Shaded values indicate the larger value when comparing like quantities for the largest and smallest UHI or cool island values.

		Diff (°C)	T_a (°C)	T_d (°C)	WS (m/s)	P (mb)
Largest	Win	1.1	0.2	-6.0	0.8	1018.7
Night	Spr	2.0	15.7	5.5	0.9	1024.1
UHI	Sum	2.3	21.6	14.1	0.7	1012.8
	Fal	2.1	17.0	12.1	0.6	1020.9
Smallest	Win	0.1	1.6	-1.3	1.8	1009.4
Night	Spr	0.1	13.3	11.8	1.5	1009.2
UHI	Sum	0.3	19.8	18.4	0.7	1011.4
	Fal	0.1	11.7	9.9	1.1	1011.7
Largest	Win	-0.2	3.3	-0.3	1.1	1011.8
Day	Spr	-0.3	18.0	12.1	0.8	1017.0
Cool island	Sum	-0.8	24.1	19.7	0.4	1015.5
	Fal	-0.5	17.7	12.8	0.4	1017.9
Smallest	Win	0.7	-1.9	-7.5	1.4	1021.7
Day	Spr	0.9	13.9	4.2	2.1	1013.3
Cool island	Sum	0.2	21.1	17.4	1.1	1012.2
	Fal	0.6	8.4	3.5	0.8	1020.6

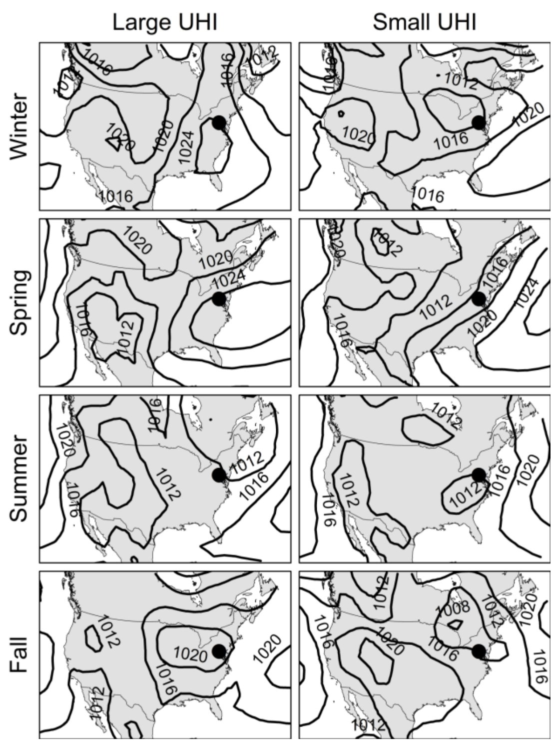

Figure 5. Composite seasonal sea level pressure maps for the ten largest and smallest urban heat island days. The circle represents the study site.

To assess the impact of rural land surface type on the UHI, Figure 6 shows the difference between UHI values for three collocated rural stations with different surface types. With a few exceptions, the difference in UHIs is ordered from largest to smallest as corn-woods, corn-grass, and woods-grass. Since all three stations used the same urban temperature to calculate the UHI value, this implies that the corn UHI is larger than the grass UHI which is larger than the woods UHI. Consequently, in general, the corn nighttime average temperature is cooler than the grass temperature, which is cooler than the woods temperature.

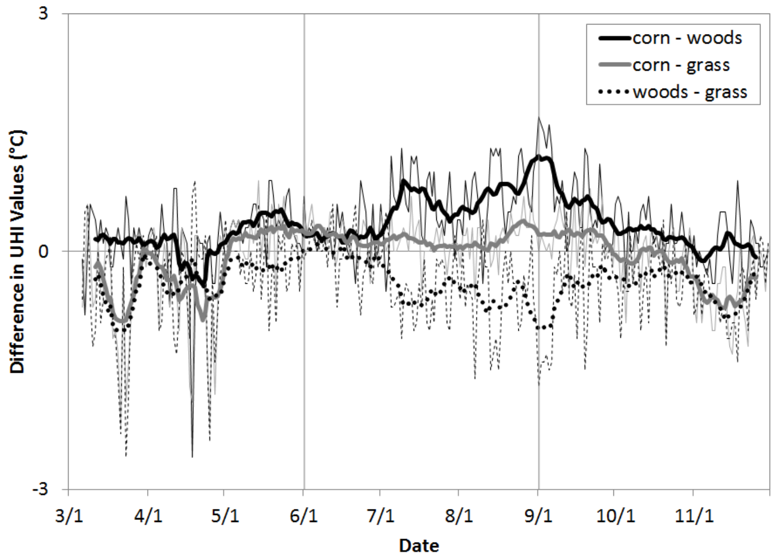

Figure 6. Difference between urban heat island values for the three collocated stations. Thin lines are daily values and thick lines are 10-day running averages. UHI values were calculated as the difference between the urban station average and each of the three collocated rural stations.

These general patterns however do evolve over the course of the study period and can generally be defined as pre-growing season (March – April), growing season (May - September), and post-growing season (October – November). During the pre-growing season, relatively little difference exists between the corn and woods UHIs while the grass has a larger UHI than both the corn and woods. Therefore, the grass is generally colder at night than the corn and woods. During the growing season, the corn UHI is bigger than both the woods and grass UHIs while the grass UHI is bigger than the woods UHI. The difference between the corn and woods and woods and grass UHIs increases in magnitude (woods is warmer than both at night) with a peak near September 1. The difference between the corn and grass UHIs stays nearly constant during the growing season. As leaf cover increases in the woods throughout the growing season, more terrestrial radiation is prevented from escaping and therefore keeps nighttime woods temperatures warmer than the corn or grass temperatures. The corn and grass UHI difference remains nearly constant through the growing season with the corn being slightly colder at night than the grass. Finally, during the post-growing season relationships revert back to a pattern that is similar to the pre-growing season. Thus, it appears that the evolution of the forest canopy within the woods land cover type is the dominant mechanism for altering the UHI.

Data from the collocated stations are also used in Table 4 to demonstrate the potential impact of changing LULC on the UHI. Current UHI values based on this analysis are displayed in the top row. These seasonal values are nearly identical to those calculated using the station data, suggesting that the use of LULC data is a viable methodology. Increasing the urbanized area from 25% to 100% within the study circle increases the UHI from 0.0°C to 0.2°C depending on the urbanization increase and season. Increases in the UHI are greatest in spring and summer.

While these increases in urbanization are realistic possibilities for future development in the area, it is more useful to look at extreme cases of complete conversion of a land cover type to better understand the impact of different land cover types. Such results may be applied to larger cities where the UHI and change in UHI due to LULC change may be more dramatic. Conversion of forest to urban was not a realistic option as the vast majority of forest is contained within a state forest and thus will not be developed. Conversion of all agricultural land to urban land use results in a 0.2°C to 0.3°C seasonal UHI increase while conversion of all grass land results in 0.3°C to 0.7°C seasonal UHI increase. Note that the grass land type is mostly farmland that is cultivated for hay or has been left fallow. The measured grass temperature at the collocated site was warmer than the measured agricultural corn temperature. Consequently, conversion of all the grass to urban results in a rural temperature that is dominated by agriculture which is slightly cooler. Conversion of both grass and agriculture to urban results in a 0.3°C to 0.7°C increase in the UHI while conversion of all rural land to urban results in a 0.5°C to 1.0°C increase in the UHI. In all cases, summer increases are greatest.

Table 4. Nighttime UHI values and the change in the UHI from current conditions based on a variety of scenarios of changing land use/land cover.

	LULC Ratio				UHI			ΔUHI		
	Urb	Agr	For	Grs	spr	sum	fal	spr	sum	fal
Current	0.16	0.36	0.17	0.31	0.9	1.2	0.7	-	-	-
25% urb increase	0.20	0.33	0.17	0.30	1.0	1.3	0.7	0.1	0.1	0.0
50% urb increase	0.24	0.30	0.16	0.30	1.0	1.3	0.7	0.1	0.1	0.0
100% urb increase	0.32	0.28	0.15	0.25	1.1	1.4	0.8	0.2	0.2	0.1
All agr to urban	0.52	0.00	0.17	0.31	1.2	1.5	0.9	0.3	0.3	0.2
All grs to urban	0.47	0.36	0.17	0.00	1.2	1.6	0.9	0.3	0.4	0.2
All agr and grs to urban	0.83	0.00	0.17	0.00	1.4	1.9	1.0	0.5	0.7	0.3
All rur to urban	1.00	0.00	0.00	0.00	1.7	2.2	1.2	0.6	1.0	0.5
All grs to forest	0.16	0.36	0.48	0.00	0.9	1.2	0.6	0.0	0.0	-0.1
All agr to forest	0.16	0.00	0.53	0.31	0.8	1.0	0.5	-0.1	-0.2	-0.2
All grs and agr to forest	0.16	0.00	0.84	0.00	0.8	1.0	0.5	-0.1	-0.2	-0.2

The final three rows of Table 4 show the impact of conversion of rural agriculture or grassland to forest. While 100% conversion is not likely, some conversion to forest is likely due to some farmland not being actively farmed or due to conscious decisions to convert farmland back to native forestland. Under these scenarios the UHI decreases 0.0°C to 0.2°C depending on the scenario and season. The measured collocated woods temperature is warmer than the grass or corn temperature and thus a conversion to forestland results in a warming of the rural environment and a decrease in the UHI.

CONCLUSION

Temperature data were collected for a year from a set of rural and urban stations around the borough of Shippensburg, PA to assess the magnitude and timing of the UHI associated with a small urban area positioned in a landscape primarily dominated by agriculture. Also examined were the role of weather type and rural land cover in determining the UHI. The results can be summarized as follows.

- On average, the UHI ranges from 0.6°C in the winter to 1.2°C in the summer with an annual average of 0.9°C. The UHI is maximized between the hours of 1800 and 0400 LST in winter, 2000 to 0200 in spring, summer and fall. A smaller daytime urban cool island exists in every season except winter during the late morning hours.
- The largest UHIs were prevalent during dry polar and dry moderate weather types for all seasons. These weather types are characterized as warm, dry, calm, and higher pressure than days with smaller UHIs. Synoptic sea level pressure maps confirm this analysis.
- Differences in temperature and therefore the UHI existed between collocated rural stations with the corn field being cooler than both a grass and wooded site at nighttime implying that rural location choice will

influence UHI calculation and that evolution of the forest over the course of the growing season has the greatest impact on the UHI from a rural standpoint.

- Applying the collocated temperature values to a LULC classification for the area indicated that the UHI may increase by as much as 1.0°C in the extreme case of complete conversion of rural land cover types to urban. The UHI increases to a lesser extent under smaller conversion rates to urban classification. Conversion of rural agriculture and grassland to forest results in up to a 0.2°C decrease in the UHI.

Results from this study, while unique to the study site, serve as a template for analyses of other small, rural cities. Factors such as rural land use type and prevailing weather types must be considered when assessing the seasonality and magnitude of the UHI. Additionally, the LULC conversion analysis may be applied to cities of any size and highlights the importance of considering the impact of LULC change and its impact on temperature and therefore the UHI. It is likely that a similar LULC analysis of a larger city would produce similar but magnified results. Although it is important to note that each urban area has its own unique features that will influence its UHI and thus it is important to catalogue as many UHIs as possible.

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