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Article

Variations in Heat Absorption and Release of Earth Surfaces During Fall in Laramie, Wyoming

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SUMMARY

All Earth surfaces absorb heat at different rates and release it afterwards. If surfaces release less heat than they absorb, they will remain warmer. Heat retained by man-made surfaces and human activities are the two major contributors of the Urban Heat Island (UHI) effect witnessed in cities worldwide. Though the effects of UHI are well studied in summer and winter months, UHI effects are not widely studied in other seasons and smaller cities. We conducted this study to document the contributions of man-made surfaces in Laramie, Wyoming to the UHI effect. Heat absorption and release by five surfaces were measured in the autumn of 2018. We hypothesized that heat retention by all surfaces will vary throughout the fall season due to differences in ambient air temperature. We recorded temperatures of man-made and natural surfaces at early morning, mid-afternoon, and evening using an infrared thermometer. Results from this study showed that man-made surfaces retained more heat in fall than natural surfaces. The amount of heat retained by all surfaces was higher in early fall and less in late fall. Presence of smoke, haze, snow, and clouds altered the pattern of heat absorption and release. Future studies could expand to other cities, include more surfaces, and measure temperature more frequently to estimate their contribution to UHI.

INTRODUCTION

Earth surfaces absorb energy emitted by the sun in the form of electromagnetic (EM) waves. These surfaces then convert the absorbed energy to heat, which increases their temperature, and release the energy later in the day or throughout the night (1). For example, bare ground absorbs sunlight in the morning and early afternoon which raises its temperature. Later in the day, bare ground releases the absorbed energy and returns to its original temperature. This radiation inflow and outflow is expressed as the surface energy budget (Equation 1):

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \quad [1]$$

where Q* is the net all-wave radiation, Q_F is the heat released by combustion, Q_H is the sensible heat flux density, Q_E is the latent heat flux density, ΔQ_S is the net heat storage, and ΔQ_A is the net heat advection (2). The net all-wave radiation, Q*, is estimated using Equation 2:

$$Q^* = K{\downarrow} - K{\uparrow} + L{\downarrow} - L{\uparrow} \quad [2]$$

where, K↓ and L↓ is the incoming short-wave and long-wave radiation respectively, K↑ is the reflected short-wave radiation, and L↑ outgoing long-wave radiation, which can be emitted and reflected by earth surfaces.

Natural surfaces such as bare ground, rocks, and vegetation release most of what they absorbed during the course of the day (3, 4). However, many man-made or built surfaces such as asphalt roads, cement sidewalks, parking lots, building roofs, steel skyscrapers, etc. release less heat than what they absorbed. This results in man-made surfaces retaining more heat, so they are relatively warmer than natural surfaces later in the day (3, 4). For example, if a surface has a starting temperature of 10 ˚C, gains 10 ˚C during the course of a day, and loses only 8 ˚C in the evening, its resulting temperature will be warmer than its starting value. Also, if man-made surfaces release less heat at night, the next day they tend to be warmer. If this process continues every day, the overall temperature of the surface will increase over a course of time.

In urban areas, natural surfaces such as bare ground and vegetation are replaced by buildings, roads, sidewalks etc. Vegetation cools the Earth's surface through a process known as evapotranspiration (4, 5). At higher temperatures, plants and trees release water through their stomata to cool themselves. This process is termed as evapotranspiration, and it cools the surrounding area (6). With less evapotranspiration, urban areas trap more heat. When more and more natural surfaces are replaced by urban infrastructure, this phenomenon is worsened. In addition to these man-made infrastructures, urban areas also generate heat from automobiles, people, industries, etc. (5). This heat is trapped in the lower levels of the atmosphere (3). As a result, urban areas retain more heat than surrounding rural areas during night time (7). This phenomenon is termed as Urban Heat Island (UHI) (4, 5, 7, 8). UHI is a problem for most cities around the world. When cities are warmer during night than surrounding rural areas, it can cause the morning (or starting) temperature to be warmer the next day. If this process continues, cities will be warmer than rural areas. As cities get warmer, the residents will use more energy to cool themselves. This increased energy usage contributes more heat to the ecosystem. This can impact many fragile ecosystems. Densely populated cities with more activities experience a higher UHI effect.

Previous studies have analyzed UHI effects and reported that this phenomenon is prevalent in many major cities throughout the world (9-11). According to a study published in 2015 (12), the following 5 US cities exhibited the most intense UHI effect: Salt Lake City, Miami (FL), Louisville, Los Angeles, and Las Vegas. Many studies have reported warmer night time temperatures in summer and winter months (10) but fewer studies have reported the pattern in autumn.

Further, not many studies have been conducted in small cities and towns to quantify the effects of UHI because they do not have many buildings and smaller population. These small urban areas can also experience the similar problems that are faced by large metropolitan areas. The combined contribution of these small cities and towns can be equivalent to several large ones. Therefore, we must study the effects of UHI in smaller cities and towns.

The objective of this study was to determine if natural and man-made Earth surfaces in Laramie, Wyoming absorbed and released heat differently during the 2018 fall season. Laramie is a small city in Wyoming (USA) with a population of approximately 32,479 (2018 estimate). We hypothesized that heat retention by surfaces will vary throughout the fall season, since the ambient air temperature will be higher in early in comparison to late fall.

RESULTS

Surface temperatures were measured in weeks 1, 2, 3, 5, 8, 12, 13, of the fall 2018 season, totaling seven weeks. No readings were recorded for the rest of the weeks since the study area was covered by ice/snow or it rained.

Smoke and haze from wildfires covered the city of Laramie in weeks one and two, which reduced the amount of sunlight reaching the surfaces (13). Clouds and smoke have similar effects, since they are made up of small particles that reflect incoming light(14). In week eight, there were thick clouds, and light snow was present on most of the surfaces. Thus, these three weeks were termed as anomalous, since the amount of heat absorbed and released was affected by the weather conditions. The rest of the weeks were considered as normal. After the data were grouped into normal and anomalous, the mean was calculated for each surface every week.

Further data were split into early and late fall, since the air temperature was higher at the start of the season (15.2 ˚C) than at the end (-4.5˚C). In early fall, the sun's rays reach the earth at a steeper angle, while in the later part of this season the rays reach at a shallower angle. This causes warmer air temperatures in early fall (15).

Normal Weeks

(i) Early fall (Weeks 3 and 5)

At the start of the day, the average temperature of each surface was lower than two degrees Celsius **(Table 1)**. At 1 pm, their temperature reached above mid-twenty degrees Celsius. By 7 pm, temperatures of the surfaces did not return to their starting values. Grass lawn was the closest to its starting temperature **(Table 1).** Standard deviation values were highest for cement sidewalk at 1 pm (most variation within the surface), and the lowest value was for pebbles at 7 am (the least variation).

Surface	Average temperature (Standard deviation)		
	7 am	1 pm	7 pm
Pebbles (n=7)	-1.2°C (0.80)	33.7°C (2.30)	6.8°C (1.64)
Bare ground (n=7)	-1.3°C (1.17)	28.6°C (1.44)	7.0°C (0.96)
Asphalt road (n=7)	1.8°C (1.32)	29.9°C (1.86)	11.6°C (1.05)
Cement sidewalk (n=7)	0.8°C (1.00)	26.9°C (2.73)	12.1°C (2.18)
Grass lawn (n=7)	-1.3°C (1.00)	27.6°C (2.28)	1.5°C (1.03)

Table 1: Temperature and standard deviation values during normal weeks in early fall. Average temperature and standard deviation values measured at 7 am, 1 pm and 7 pm in early fall (weeks 3 and 5) under clear weather conditions. Temperature values were measured at 7 locations for each of the five surfaces, and their average and standard deviation values were computed.

Results from the *t*-test with Bonferroni corrected alpha value of 0.0167, indicated that the average temperature measured for pebbles, asphalt road, and cement at 1 pm was significantly higher ($p < 0.001$) than their 7 am values. Similarly, the average temperature of each surface dropped by 7 pm, and that value was significantly lower ($p < 0.001$) than 1 pm. The 7 am and 7 pm temperatures were significantly different ($p < 0.001$).

The average maximum air temperature for the normal early fall weeks (3 and 5) was 12.8˚C. Pebbles and bare ground absorbed and released different amounts of heat but retained approximately similar amounts **(Figure 1a).** Pebbles gained 34.9˚C and released 26.9˚C, and bare ground gained 29.9 ˚C and released 21.6 ˚C. The net heat gain of pebbles was 8.0˚C and bare ground was 8.3˚C.

Among man-made surfaces, asphalt road absorbed and released the most heat **(Figure 1a)**. Asphalt gained 28.1˚C in the AM and lost 18.3˚C in the PM. Asphalt's net heat gain was 9.8˚C. For cement sidewalk, the absorption was 26.1˚C and the release was 14.8˚C, resulting in a net gain of 11.3˚C. Among the two man-made surfaces, cement sidewalk retained the most heat at the end of the day.

Grass lawn released nearly as much heat as it absorbed **(Figure 1a).** Grass lawn gained 28.9 ˚C (AM gain) and lost 26.1 ˚C (PM loss) resulting in a net heat gain of 2.8 ˚C.

(ii) Late fall (Weeks 12 and 13)

At the start of day, the average temperature of each surface was below 0˚C **(Table 2).** At 1 pm, surface temperatures did not exceed 8˚C. Surface temperatures at 7 pm were very close to their respective starting values at 7 am. Standard deviation values were highest for pebbles at 1 pm (most variation within this surface), and the lowest value was for cement sidewalk at 7 pm (least variation). The variation in the temperature readings **(Table 2)** was higher in late fall in comparison to the corresponding values in early fall **(Table 1).**

Surface	Average temperature (Standard deviation)		
	7 am	1 pm	7 pm
Pebbles (n=7)	-10.5˚C (4.05)	5.6˚C (5.40)	-10.2˚C (2.99)
Bare ground (n=7)	N/R	N/R	N/R
Asphalt road (n=7)	-10.2˚C (3.38)	7.7˚C (3.05)	-10.0˚C (2.88)
Cement sidewalk (n=7)	-11.3˚C (3.45)	4.5˚C (4.42)	-8.0˚C (2.37)
Grass (n=7)	N/R	N/R	N/R

NOTES: N/R – Not recorded

Table 2: Temperature and standard deviation values during normal weeks in late fall. Average temperature and standard deviation values measured at 7 am, 1 pm and 7 pm in late fall (weeks 12 and 13) under clear weather conditions. Temperature values were measured at 7 locations for each of the five surfaces, and their average and standard deviation values were computed.

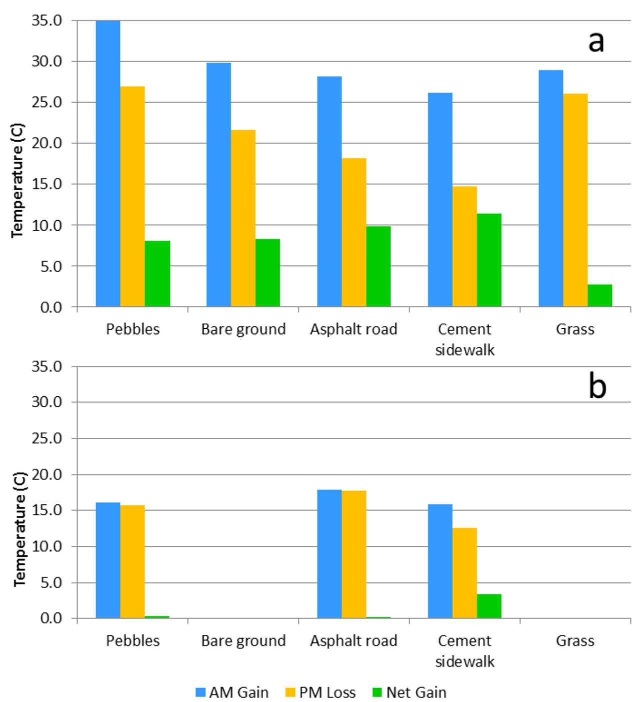

Figure 1: Heat gained, released, and retained by five surfaces in early (a) and late (b) fall. The heat gained (blue bar) between 7 am and 1 pm and released (yellow bar) between 1 pm and 7 pm shows that man-made surfaces (asphalt road and cement sidewalk) retained more heat (green bar) than the natural surfaces and grass lawn. In late fall only cement sidewalk retained some heat that it gained during the day. No readings were taken for bare ground and grass since they were covered in snow.

Results from the *t*-test indicated that the average temperature measured for each surface at 1 pm was significantly higher ($p < 0.001$) than their 7 am values. Similarly, the average temperature of each surface dropped by 7 pm, that value was significantly lower ($p < 0.001$) than 1 pm. However, the 7 am and 7 pm values were not significantly different ($p < 0.05$) for asphalt and pebbles. For cement sidewalk, the values were still significantly different ($p < 0.01$).

The average maximum air temperature for the normal late fall weeks was 3.6 ˚C. Among the natural surfaces, readings were measured only for pebbles since bare ground was covered by snow. Pebbles absorbed 16.1˚C and released 15.8˚C, thus retaining 0.3˚C **(Figure 1b).**

Among the man-made surfaces, cement sidewalk had the highest net heat gain. Asphalt's AM gain and PM loss was 17.9˚C and 17.7˚C, respectively. Asphalt's net heat gain was 0.2˚C. For cement sidewalk, the absorption was 15.8˚C and its release was 12.5˚C; resulting in a net heat gain of 3.3˚C **(Figure 1b)**.

No readings were taken for grass lawn as the surface was covered by snow.

Anomalous Weeks

(i) Early fall (Weeks 1 and 2)

Surface	Average temperature (Standard deviation)		
	7 am	1 pm	7 pm
Pebbles (n=7)	4.3˚C (1.24)	34.0˚C (2.18)	15.1˚C (0.89)
Bare ground (n=7)	6.7˚C (0.70)	33.8˚C (1.08)	15.8˚C (0.61)
Asphalt road (n=7)	10.2˚C (0.58)	32.7˚C (0.82)	19.6˚C (0.39)
Cement sidewalk (n=7)	7.9˚C (0.77)	27.6˚C (2.43)	19.1˚C (0.82)
Grass (n=7)	1.8˚C (1.16)	25.1˚C (2.69)	9.2˚C (1.54)

Table 3: Temperature and standard deviation values during anomalous weeks in early fall. Temperature and standard deviation values during anomalous weeks in early fall. Average temperature and standard deviation values measured at 7 am, 1 pm and 7 pm in early fall (weeks 1 and 2) under smoke and hazy conditions. Temperature values were measured at 7 locations for each of the

The average maximum air temperature for the early fall weeks with smoke and haze was 24.2˚C. Smoke and haze from a wildfire near the study area were present in weeks 1 and 2. The amount of sunlight that reached the surfaces was limited due to the presence of smoke (12).

Among natural surfaces, pebbles had the highest absorption and release. Pebbles' AM gain was 29.7˚C and their PM loss was 18.9˚C. The net heat gain was 10.8˚C **(Figure 2).** For bare ground, the absorption was 27.1˚C and its release was 18.0˚C. Bare ground's net heat gain was 9.1˚C **(Figure 2).**

Among man-made surfaces, asphalt had the highest absorption and release. For asphalt, the AM gain was 22.5˚C and its release was 13.1˚C. Asphalt's net heat gain was 9.4˚C **(Figure 2)**. For cement sidewalk, the absorption was 19.7 ˚C; the release of cement sidewalk was 8.5˚C. Cement sidewalk's net heat gain was 11.2˚C **(Figure 2).**

Unlike weeks 3 and 5 (clear conditions), grass lawn did not release as much heat as it absorbed under smoke and haze conditions. The AM gain was 23.3˚C and the PM loss was 15.9˚C. Grass lawn's net heat gain was 7.4˚C **(Figure 2).**

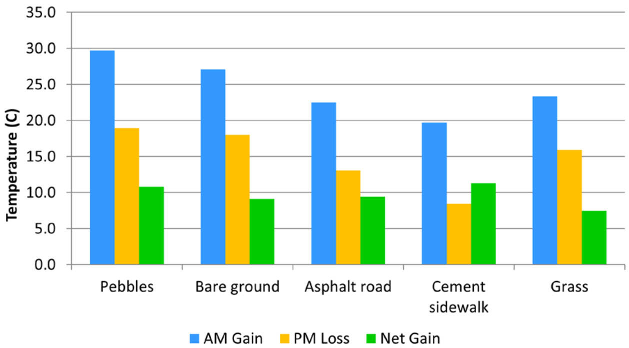

Figure 2: Heat gained, released, and retained by five surfaces in early fall under smoke and hazy conditions. The heat gained (blue bar) between 7 am and 1 pm and released (yellow bar) between 1 pm and 7 pm shows that pebbles and cement sidewalk retained more heat (green bar) than the rest of the surfaces. Man-made surfaces gained less heat than the natural surfaces.

(ii) Late fall (Week 8)

Surface	Average temperature (Standard deviation)		
	7 am	1 pm	7 pm
Pebbles	-6.9˚C (1.26)	4.9˚C (0.93)	-16.4˚C (1.26)
Bare ground	-10.6˚C (1.59)	2.8˚C (0.53)	-9.0˚C (0.99)
Asphalt road	-4.6˚C (1.45)	6.0˚C (0.45)	-12.1˚C (0.53)
Cement sidewalk	-4.9˚C (1.37)	5.1˚C (0.81)	-9.1˚C (0.30)
Grass	-10.1˚C (0.47)	0.6˚C (1.64)	-13.6˚C (1.60)

Table 4: Temperature and standard deviation values during anomalous week eight. Average temperature and standard deviation values measured at 7 am, 1 pm and 7 pm in early fall (week 8) under heavy cloud cover and light snow conditions. Temperature values were measured at 7 locations for each of the five surfaces, and their average and standard deviation values were computed.

The maximum air temperature was -5.6 ˚C for the late fall week. In week 8, snow, cloud cover, and windy conditions were present, hence the air temperature was noticeably cooler than normal weeks (3 and 5). All surfaces, except bare ground, released more heat than what they absorbed.

Among natural surfaces, bare ground had the highest absorption and the lowest release. For bare ground, the absorption was 13.4˚C and its release was 11.8˚C. The net heat gain for bare ground was 1.6˚C **(Figure 3)**. Pebbles absorbed (AM gain) 11.8˚C, released 21.3˚C (PM loss), hence the net heat loss was 9.5˚C **(Figure 3).**

Among man-made surfaces, asphalt both absorbed and released the most heat. For asphalt, the absorption and release were 10.6˚C and 18.1˚C respectively. The net heat loss of asphalt was 7.5˚C. Cement sidewalk's absorption was 10.0˚C and its release was 14.2˚C. Cement sidewalk's net heat loss was 4.2˚C. Under snow, cloud cover, and windy conditions, cement sidewalk had the highest net heat gain in comparison to asphalt road **(Figure 3)**.

In week 8, grass lawn actually had the lowest net heat loss of 3.5˚C. The absorption and release were 10.7˚C and 14.2˚C, respectively.

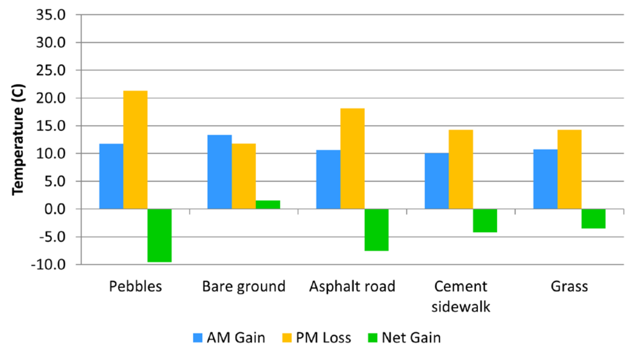

Figure 3: Heat gained, released, and retained by five surfaces on a cloudy day in late fall. The heat gained (blue bar) between 7 am and 1 pm and released (yellow bar) between 1 pm and 7 pm shows that all surfaces except bare ground released more heat than they absorbed.

DISCUSSION

This study shows that man-made features in Laramie, WY retained more heat during the first five weeks of fall 2018. Later in the fall season, the amount of heat retained by man-made surfaces was lower. This excess heat retained by these surfaces increases the ΔQ_S, the net heat storage in the surface energy budget equation. This study shows that man-made features in a small city are contributing to UHI in fall. This effect present in small urban areas may appear small, but when added up they could also have a big impact on a state's or region's UHI. Therefore, scientists should monitor smaller urban areas during fall season.

The results of this study support the hypothesis that man-made surfaces retain more heat than natural surfaces in the fall season. As hypothesized, there was also a variation in the amount of heat retained throughout the fall season. During normal early fall weeks, when the maximum ambient temperature was 12.8˚C, surfaces retained more heat than in late fall, when maximum ambient temperature was 3.6˚C.

The maximum ambient temperature for the first 2 weeks was much higher (24.2˚C), but the surface heat retention was only slightly higher than what was observed in weeks 3 and 5. The presence of smoke and haze in those weeks could have reduced the amount of incoming radiation.

In this study, cement sidewalk retained the most heat in all weeks except when all surfaces were covered by thick cloud cover and high winds (week 8). As reported by NASA, dark surfaces absorb almost all light and convert it into heat (16). The more light surfaces absorb, the more heat they emit. Lighter surfaces, on the other hand, reflect almost all light, therefore they do not emit as much heat (16, 17). Man-made surfaces retained more heat than natural surfaces, due to the materials present in them. Asphalt road, the darkest surface in this study, retained less heat than cement sidewalk, most likely due to its color. Cement sidewalk always absorbed the least amount of heat, but it released even less. Among all surfaces, cement sidewalk retained the most heat.

Natural surfaces released most of the energy they absorbed. Pebbles released most of the heat they absorbed. Bare ground, which is a lighter surface, had a higher net heat gain than pebbles. In summary, light colored cement sidewalk and bare ground retained relatively more heat than the corresponding darker surfaces in each category (16, 17). Grass lawn was always cooler than all other surfaces, except in anomaly week eight (snow, cloud cover, and windy conditions). Plants transpire and naturally cool the surrounding area. Hence, many cities are adapting to the idea of green roofs on buildings to reduce their UHI effect. This idea is that plants are planted on roofs to help maintain a cooler temperature.

In this study, there could have been some sources of error that could have influenced the outcome. One source of error could have been changes in the pattern of weather and shadows within a day. Small changes in temperature and other weather factors could have influenced the absorption of the surfaces. Shadows may be another source of error as they change throughout the day, due to the movement of the sun. Shadows would cool the area they are shading, which would influence the temperature reading. In this study, this was avoided these problems by selecting areas that were not surrounded by objects (parked vehicles, trees, road signs, and buildings) that would shade them.

On windy days, there will be a difference in the convection pattern (18). On non-windy days, heat rises vertically (convection), whereas on windy days the process occurs horizontally (advection,19). Advection does not allow surfaces to be heated as they normally would have under non-windy conditions. Therefore, on windy days multiple readings much be taken at each sample point and the average value must be recorded.

When smoke from nearby wildfires covered the study area in weeks 1 and 2, surfaces absorbed and released less energy. This was due to the absorption and scattering of incoming sunlight by aerosols present in the smoke (13). Under smoke and cloud conditions, less sunlight reached the surfaces.

To further confirm the findings of this study, additional readings must be taken in normal, windy, cloudy, and hazy conditions in fall season. Readings should also include a larger variety of surfaces of various colors and textures. Sites must be selected to avoid chances of being covered in shadows as an abundance of buildings, trees, fences, etc. in or near the site may affect the temperatures of the sample points. This study could be expanded to other cities and towns in Wyoming to further assess the contribution of man-made features to UHI.

MATERIALS AND METHODS

In 2018, the fall season started on September 22 and ended on December 21 (nasa.gov). The first and last readings were recorded on September 23 and December 16, respectively.

Five earth surfaces were selected for this study: bare ground and pebbles (natural), asphalt road and cement sidewalk (man-made), and grass lawn (live). Bare ground was a light brown color **(Figure 4a)** and pebbles were medium to dark shades of gray **(Figure 4b).** The asphalt road was dark grey in color **(Figure 4c),** and the cement sidewalk was light tan in color **(Figure 4d).** Grass was mostly green **(Figure 4e)** at the start of the fall season and gradually changed to yellow and light brown colors by the end of the season. These surfaces chosen were not shaded by trees, fences, buildings, parked vehicles, etc., and received more or less the same amount of sunlight each day during the study.

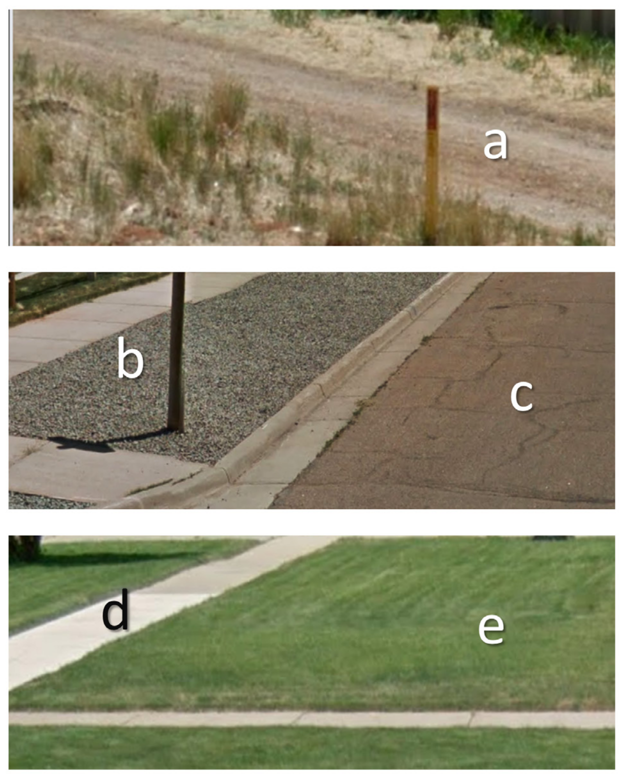

Figure 4: Natural and man-made surfaces included in this study. Two natural surfaces were light brown bare ground (a) and grey colored pebbles (b). Two man-made surfaces included dark grey asphalt road (c) and light colored cement sidewalk (d). Grass lawn (e) was the live surface.

Surface temperatures were measured using a Fluke© 63 Infrared Thermometer (Everett, WA). This thermometer is recommended by NASA's GLOBE program (20) and can accurately measure temperatures ranging from -32 ˚C to 535 ˚C (www.fluke.com). For measuring the temperature of any surface or object, this instrument has to be pointed towards it. The area in which the temperature is being taken will be highlighted when the trigger is pressed. The digital display will show the temperature in either in Fahrenheit or Celsius, based on the user preference. This instrument was used to take readings on weeks 1, 2, 3, 5, 8, 12, and 13. No readings were taken during the rest of weeks when the weather conditions were windy, cloudy, snowy, etc.

Sundays were selected as sampling days. On that day, the first set of temperature readings was recorded shortly before sunrise, approximately between seven and eight AM. Prior to the reading, the starting time, along with the air temperature and weather conditions were recorded. One of the five surfaces was randomly selected, and its temperature was measured at 7 different locations that were at least 0.5 m apart. This step was repeated for the remaining four surfaces. After all readings were recorded (7 locations x 5 surfaces = 35 readings), the ending time was noted. The second and third set of temperature readings for each sampling day were taken after six hours (between 1 and 2 PM) and twelve hours (between 7 and 8 PM) starting from the first reading, respectively. At the end of a sampling day, we collected 105 readings/sampling day (35 readings x 3 times/day). The day-time high temperature for each observation day was recorded from the Weather Underground (21).

During weeks 1 – 3, 5, and 8 readings were recorded for all five surfaces. However, in weeks 12 and 13, readings were not recorded for bare ground and grass lawn because they were covered in snow and ice.

For each surface, average temperature and standard deviation values were calculated for morning (7 am), afternoon (1 pm), and evening (7 pm) values using Microsoft Excel™. This step was repeated for the remaining surfaces. Temperature measurements were compared for a) increase (between 7 am and 1 pm), b) decrease (between 1 pm and 7 pm), and c) net gain (between 7 am and 7 pm) using one tailed *t*-test. Since three comparisons were made with the temperature measurements we applied Bonferroni correction to the alpha value of 0.05:

$$\alpha_{corrected} = \alpha / c \quad [3]$$

where, α = 0.05, and c= 3 (number of comparisons). Bonferroni correction reduces the likelihood of reporting significant results by chance alone. In this study we used the adjusted alpha value of 0.01667. This test showed whether the afternoon temperature for each surface was statistically different from its morning or evening temperatures.

The average temperature value measured at 7 am was subtracted from the average value measured at 1 pm and was termed as AM heat gain.

AM heat gain = Average afternoon temperature – Average morning temperature [4]

Similarly, the afternoon heat loss was termed as the difference between the afternoon and evening temperatures.

PM heat loss = Average afternoon temperature – Average evening temperature [5]

Difference between the morning heat gain and afternoon heat loss was termed as net heat gain or retained.

Net heat gain =AM heat gain – PM heat loss [6]

Average temperature value of each surface at 7 am, 1 pm, and 7 pm was used for estimating the AM gain, PM loss, and Net gain for each sampling day.

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