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SURFACE TEMPERATURE, HEAT LOADING AND SPECTRAL REFLECTANCE OF ARTIFICIAL TURFGRASS

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SUMMARY

In the arid southwestern United States, artificial turfgrass is being considered as a water conserving alternative to living turfgrass for sporting fields and parks. However, a potentially significant undesirable characteristic of artificial turfgrass is the elevated surface temperatures that occur during daylight hours. The objective of this study was to examine the factors that influence surface temperature rise of artificial turfgrass (Geneva "Grid Iron Supreme"). The data collection included: surface temperature, spectral reflectance, solar radiation and air temperatures associated with different landscape covers and artificial turfgrass components; and, an assessment of energy balance and heat transport through artificial turfgrass. The study was conducted in Las Vegas, NV, USA. Results showed surface temperatures on green artificial turfgrass with black rubber infill as significantly higher ($P<0.05$) than white artificial turfgrass, asphalt, bare soil, concrete, and living turfgrass, with maximum surface temperatures of 76°C. Solar radiation accounted for most of the variation in surface temperature of the green artificial turfgrass ($r^2=0.95$, $P<0.001$) as opposed to air temperature ($r^2=0.32$; $P<0.05$). Spectral reflectance measurements showed green artificial turfgrass reflecting less than 10% of incoming radiation (wavelengths ranging from 350-2500 nm). Average reflectance in the near-infrared region (701-1300 nm) was shown to be significantly correlated with surface temperature of different landscape surfaces ($r^2= 0.62$, $P<0.05$). Sensible heat flux from the turf surface accounted for more than 90% of incoming solar radiation, with the remainder of the energy conducted into the soil. We recommend that similar measurements be made on other products before installation. Our data would also support the development of empirical relationships between solar radiation and surface temperatures as a way of managing when recreational fields can be safely used.

INTRODUCTION

Artificial turfgrass has been used as a substitute for living turfgrass since the mid 1960s, when it was first introduced in the Houston Astrodome (Culpepper 1986). The rationale for switching to artificial turfgrass since that first installation has varied based on site location and user needs. Reasons have included: increasing playability during inclement weather, low maintenance costs, and perhaps most relevant to the southwestern United States, the conservation of water. Although the first and third reasons are agreeable to most, the second reason has been disputed by others (Brakeman 2005).

Urban areas throughout the southwestern United States have increased rapidly in population during the last few decades. The population in southern Nevada, in particular, sisted of surface temperature (three measurements per site) with an infrared thermometer (Cole Parmer Model 39800); solar radiation with a pyranometer (LiCor Model 200); and, air temperature and relative humidity at a 60 cm height above the artificial turfgrass with a combination sensor (Omega, model RH71). Measurements were acquired at sites 1-6 following the same order each hour, with all measurements obtained within a 20-minute time period. At 13:00 on the same day, spectral reflectance was measured on all six surfaces. A spectroradiometer (Fieldspec 3, Analytical Spectral Devices, Boulder, CO) was used to obtain spectral reflectance measurements over the electromagnetic spectral range of 350 to 2500 nm at a fixed 25° field of view. The sampling interval was 1.4 nm for the region 350-1000 nm and 2 nm for the region 1000-2500 nm. The spectral resolution was 3 nm for the region 350-1000 nm and 10 nm for the region 1000-2500 nm. The instrument was calibrated with a white standard prior to measurements and was internally calibrated after every six data acquisitions. The spectral measurements (5 spectral readings averaged) coincided with the 13:00 surface temperature measurements acquired during the surface temperature diurnal.

Surface temperature of artificial turfgrass components

On 12 October 2006 hourly surface temperatures were measured on eight different surfaces consisting of various components of an artificial turfgrass system. The components studied included: 1) black rubber beads; 2) white rubber beads; 3) artificial turfgrass with no rubber beads; 4) black rubber matting with no artificial turfgrass blades; 5) artificial turfgrass with black rubber beads; 6) artificial turfgrass with white rubber beads; 7) artificial turfgrass cuttings; and 8) sandy loam soil (bare). The artificial turfgrass was a Geneva "Grid Iron Supreme." The rubber beads were of the same particle size distribution as used on the artificial turfgrass at the park location. White rubber beads were fashioned by painting black (cryogenic) rubber beads with high-temperature white enamel paint (Zynolyte, Carson, CA) until all surfaces were uniformly white, requiring over eight applications. Rubber beads (black and white) were placed on the soil surface to a thickness of 2.5 cm. The mounds of rubber beads were approximately 10 cm in diameter. The black rubber matting with no artificial turf was obtained by cutting off all synthetic turfgrass blades and removing all connections to the underlying matting. The exposed matting was approximately 0.37 m^2 in area placed directly on the bare soil. The artificial turf cuttings which were removed from the underlying black rubber matting were placed to a thickness of 2.5 cm in a horizontal fashion on the bare soil (approximately 0.09 m^2 in area). Rubber beads (black and white) were packed at 1.52 kg m^{-2} in the artificial turfgrass. All artificial turfgrass surfaces with and without rubber beads were 0.37 m^2 in area and placed directly on the bare soil. The temperatures were measured from 08:00 until 18:00. Measurements were taken hourly and consisted of surface temperature with an infrared thermometer, solar radiation with a pyranometer, and air temperature and relative humidity with a combination sensor (models are identical to those listed above). Measurements were acquired on the eight surfaces (60 cm spacing between surfaces, three measurements per surface) following the same order each hour, with all hourly measurements obtained within a 5-minute time period.

Energy balance and heat transport through artificial turfgrass

On 31 August 2006, a test plot of artificial turfgrass (4 m by 4 m, installed one year prior to the study) maintained by the City of Las Vegas Department of Park Maintenance was used to assess energy balance and transport through the artificial turfgrass. The test plot increased by 67% during the 1990s (U.S. Census Bureau). Such growth has placed increased pressure on available water resources in southern Nevada, as it has in other large rapidly growing urban areas such as Albuquerque, Phoenix, and San Antonio (Water Resource Advocates 2004). Communities like Las Vegas have spent millions of dollars replacing turfgrass on recreational sporting fields with artificial turfgrass, with the goal of reducing maintenance costs, and saving significant amounts of money by eliminating irrigation (Steve Ford, City of Las Vegas, personal communications). However, a significant undesirable characteristic that has created concern amongst park managers is the elevated surface temperature associated with artificial turfgrass. Although the rapid increase in surface temperature in the presence of sunlight has been known for decades (Buskirk *et al.* 1971, Kandelin *et al.* 1976, Ramsey 1982), little research has been published on the subject, especially related to the controlling forces behind the rise in temperature. The majority of information currently available on elevated surface temperature of artificial turfgrass has come from unpublished studies available from internet web sites, most notably the work of McNitt (2006) and Williams & Pulley (2006).

The objectives of this research were to: 1) quantify the temperature rise of different landscape surfaces and develop empirical relationships with solar radiation; 2) evaluate the surface temperature rise of different artificial turfgrass components; 3) assess the change in spectral reflectance of different landscape surfaces over wavelengths ranging from 350 to 2500 nm; and 4) quantify energy loading on artificial turfgrass and subsequent transport of heat to the underlying fill material.

MATERIAL AND METHODS

Three separate experiments were conducted during the period from August to March 2007 in Las Vegas, NV, USA, including: 1) Monitoring surface temperature on an hourly basis (diurnal) on multiple landscape surfaces at a recreational field in the City of Las Vegas; 2) Monitoring surface temperature on an hourly basis (diurnal) on eight different surfaces consisting of various components of an artificial turfgrass system at the University of Nevada Las Vegas green house complex; and 3) A 40-day monitoring of energy loading and heat transport through artificial turfgrass on a test plot installed and maintained by the City of Las Vegas Department of Park Maintenance.

Surface temperature diurnal on landscape surfaces

On 21 August 2006, from 07:00-19:00, surface temperatures were measured on six different surfaces at Ed Fountain Park located in the City of Las Vegas, NV, USA. The six surfaces monitored included: 1) green artificial turfgrass; 2) white artificial turfgrass (boundary striping); 3) sandy loam soil (bare); 4) concrete; 5) asphalt; and 6) turfgrass (common bermudagrass, *Cynodon dactylon* (L.) *pers.*). The bermudagrass maintained under city park conditions, was deemed healthy with an acceptable green appearance (visual color rating of 8.8 on a scale of 1 to 10). Additional hourly temperature data was collected on 2 March 2007 from 8:00 until 17:00 but only on the green artificial turfgrass. The artificial turfgrass was a Geneva "Grid Iron Supreme" made of Thiolon® fiber, 10,000 denier, 5.7 cm pile height, 0.95 cm gauge, 0.74 kg polyurethane coating with a face weight of 1.19 kg. The rubber infill was cryogenic rubber packed at 1.52 kg m^{-2}. The fill material below the artificial turfgrass consisted of approximately 15 cm of Type 2 aggregate base (sorted gravel mix) compacted to approximately 95%.

Measurements were taken hourly and conwas constructed in an identical fashion as the recreational field at Ed Fountain Park. The artificial turfgrass was a Geneva "Grid Iron Supreme."

Instruments used to measure energy balance included a net radiometer (Radiation and Energy Balance Systems, model Q-7.1), which was positioned on a tower at a height of 1 m above the artificial turfgrass surface. Ground conduction was determined using a soil heat flux plate (model HFT01, Hukseflux Inc, Delft, The Netherlands) installed at an 8-cm depth in the fill material, a water content reflectometer (model CS-616, Campbell Scientific Inc., Logan, UT) installed a 5 cm depth to measure the soil volumetric water content (m^3/m^3) above the soil heat flux plate, and an averaging thermocouple (model TCAV, Campbell Scientific Inc.) installed at depths of 2 and 6 cm to assess the energy stored in the fill material. After installation, the artificial turfgrass with rubber beads was repositioned and pinned in place with metal pins. All wires were terminated in an environmental enclosure that contained the data logger (model 23X, Campbell Scientific, Inc.). The logger itself was grounded to reduce risks of damage from electrical storms. Power to the logger and the instruments was provided by a deep cell marine battery that was placed in a plastic box. Data were collected every second and averaged every 5 minutes. Data collection began on August 31, 2006 and continued through 9 October 2006 for a period of 40 days.

Data were analyzed by closing the energy balance, which is expressed as:

$$Rn - L_eE - H - G = 0$$

where Rn is the net radiation (W m^{-2}), L_eE is the latent heat flux (W m^{-2}), L_e is the latent heat of vaporization (J kg^{-1}), E is the rate of evaporation (kg m^{-2} s^{-1}), H is the sensible heat flux (W m^{-2}), and G is the ground heat flux (W m^{-2}). Because the artificial turf surface does not transpire and assuming that soil water evaporation is negligible (reasonable given dry summer conditions in Las Vegas), we assume that L_eE is nil. We can rearrange the Equation (1) to obtain energy balance closure, yielding H = Rn - G. The magnitude of H represents the heat given off by the artificial turf surface.

Additionally, three copper-constantin thermocouples (model PR-T-24-SLE, Omega, Stamford, CT) were installed and placed immediately below the turfgrass matting, at the base of the artificial turfgrass blades, and at the top of the artificial turfgrass blades. This small suite of thermocouples was used to measure temperature gradients to ascertain where the heat build-up was occurring. Data collected from thermocouples were compared to a reference thermocouple inside the data logger.

All data were analyzed using descriptive and linear regression analysis (SigmaStat 3.1 2004). Only data that met the $P<0.05$ level of probability are reported.

RESULTS

Surface temperature measured on landscape surfaces

Solar radiation, air temperature and surface temperatures are plotted in Fig. 1 for the 12 hour monitoring period conducted at Ed Fountain Park in August 2006. Solar radiation followed a bell shaped curve, with maximum values of 980 W m^{-2} occurring between 12:00 and 13:00 hours. However, between 14:45 and 16:15 cloud cover reduced solar radiation to 115 W m^{-2}. Based on cloud cover and time of day, this represented an 81% reduction in solar radiation. Air temperature measured at a height of 60 cm rose steadily over the first seven hours, reaching a maximum recorded value of 44.5°C around 14:00 hours. Air temperatures fell during the 90-minute cloud cover period, with a recorded

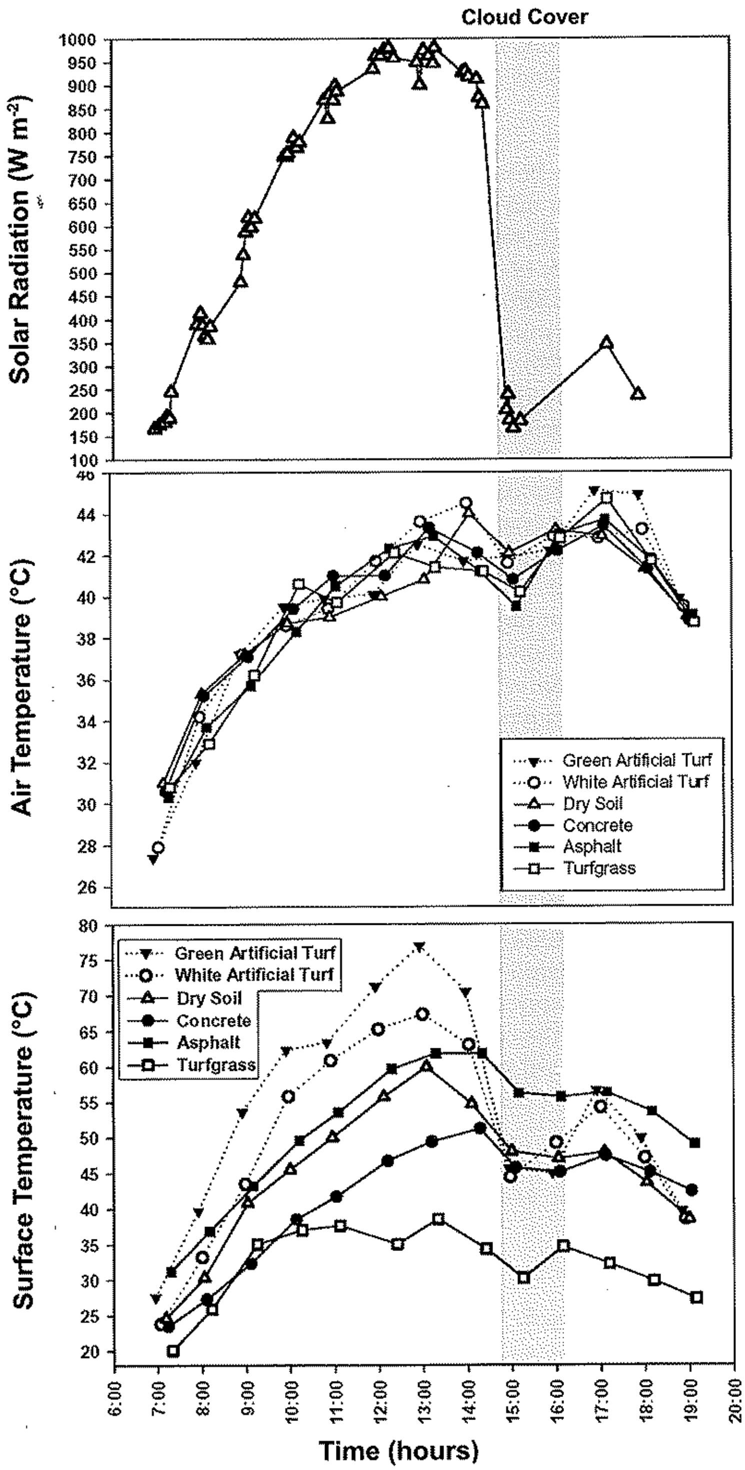

FIGURE 1. Solar radiation (A), air temperature (B), and surface temperature (C) as a function of time at Ed Fountain Park in Las Vegas, NV on 12 August 2006.

value as low as 39.5°C around 15:00 hours. Once the cloud cover passed, temperatures rose again to 45.1°C (113°F) around 17:00 hours and then fell to as low as 38.7°C during the last measurement period, which began at 19:00. Temperatures of all surfaces peaked between 13:00 and 14:00 hours, with clear separation in both the slope and the maximum values obtained ($P<0.05$). The highest temperatures were obtained on the green artificial turfgrass followed by the white artificial turfgrass, asphalt, bare soil, concrete and turfgrass (Fig. 1). The highest value recorded was 76.0°C (169°F) on the green artificial turfgrass at 12:56.

Maximum recorded temperature of green artificial turfgrass was 38.4°C higher than the irrigated turfgrass and 34.4°C higher than air temperature. Maximum recorded temperature of white artificial turfgrass was 9.6°C cooler than maximum recorded temperature of green artificial turfgrass. However, temperature of the white artificial turfgrass was still 5.5°C hotter than asphalt. Although temperatures of all surfaces declined during the 90 minute cloud cover period, the greatest declines were observed with the green and white artificial turfgrass. Between the hours of 14:00 and 15:00, temperature of the green artificial turfgrass dropped 24.9°C (36%↓), while white artificial turf dropped 18.6°C (30%↓). These declines in temperature were in stark contrast with declines observed with asphalt (5.6°C, 10%↓), concrete (5.5°C, 12%↓) and air temperature (2.9°C, 5%↓). Once the cloud cover passed, temperatures increased on all surfaces except the living turfgrass. The green artificial turfgrass increased 25.8% compared to white artificial turfgrass which increased 10.2%, concrete 5.1%, bare soil 1.9% and asphalt 1.1%.

Surface temperatures were plotted as a function of solar radiation in Fig. 2. Surface temperature increased with solar radiation load.

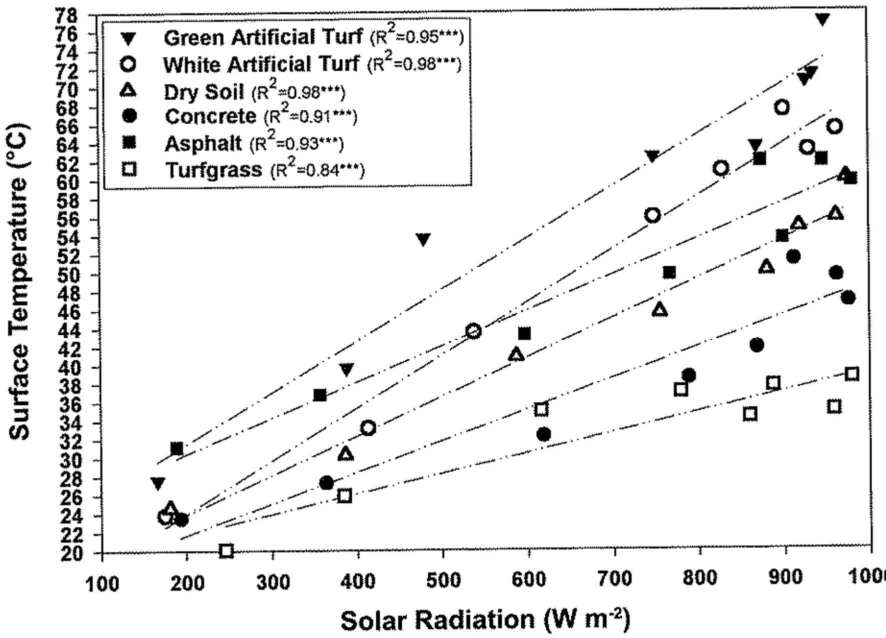

FIGURE 2. Temperatures of different surfaces as a function of solar radiation measured at Ed Fountain Park in Las Vegas, NV on 12 August 2006.

All surfaces demonstrated a linear relationship between temperature and solar radiation, even when radiation declined toward the end of the day. The decline in surface temperature associated with cloud cover did not deviate substantially from the surface temperature-solar radiation relationship based on clear sky conditions. In the case of the artificial turfgrass systems, we could account for 95% of the variation in the surface temperature of the green artificial turfgrass ($P<0.001$), and 98% of the variation in the surface temperature of the white artificial turfgrass ($P<0.001$) based solely on the measurement of solar radiation. When surface temperature was regressed against air temperature, excellent linear relationships existed only for the concrete and asphalt ($r^2>0.88$, $P<0.001$). However, for the green artificial turfgrass, only 32% of the variation ($P<0.05$) in the surface temperature could be accounted for based on the air temperature.

Spectral reflectance from multiple surfaces at park site

Spectral reflectance measured on all six surfaces at Ed Fountain Park are shown in Fig. 3. Reflectance associated with the green artificial turfgrass was consistently low over all regions of the electromagnetic spectrum (high energy absorption). This response was observed only with green artificial turfgrass and black asphalt, where reflectance values were less than 10% in all of the larger electromagnetic classes (blue, green, red, near infrared (NIR) and short wave infrared (SWIR), Table 1). Spectral reflectance of natural turfgrass demonstrated the classic response shown

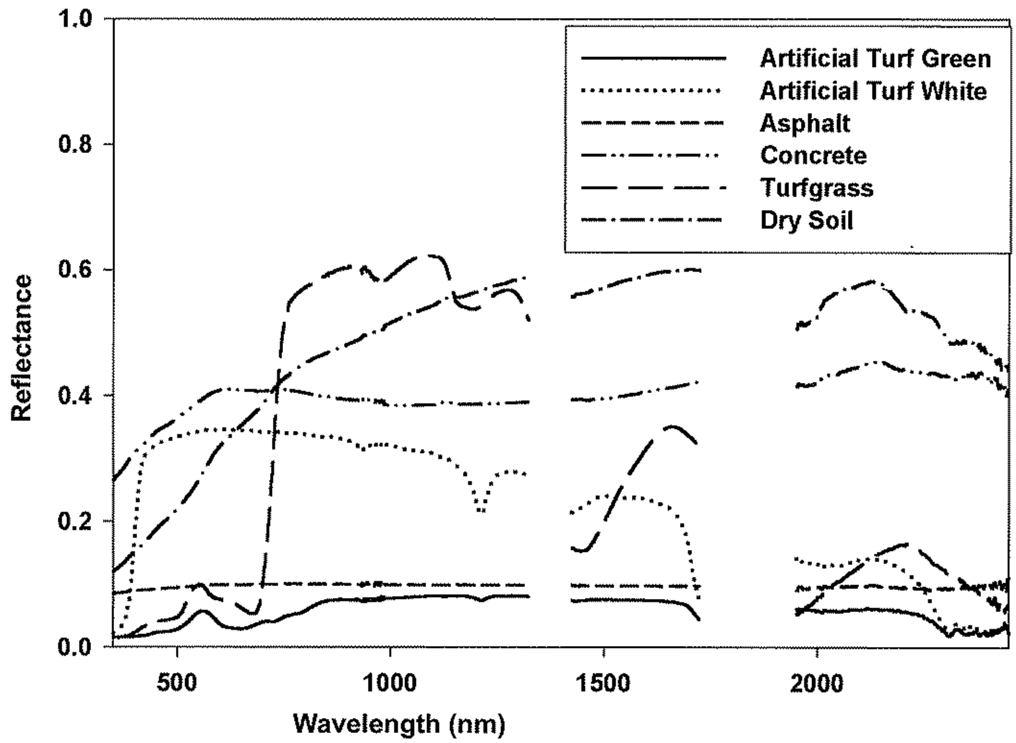

FIGURE 3. Spectral reflectance of six different surfaces as a function of wavelength.

by green vegetation (Baghzouz *et al.* 2006), with reflectance low in the blue (450-520 nm) and red (600-700 nm) regions of the electromagnetic spectrum. In addition, the natural turfgrass revealed a steep red edge effect in the 600-700 nm region followed by a plateau in the near infrared region (700-1300 nm). White artificial turfgrass had a significantly greater ($P<0.05$) amount of reflectance than green artificial turfgrass in the green, red and NIR regions. Concrete and bare soil revealed significantly higher reflectance ($P<0.05$) over the 1300-2500 nm region compared to all other surfaces.

Average reflectance over each region of the electromagnetic spectrum (blue, green, red, NIR, SWIR) in Table 1 was regressed against surface temperature. A clear separation in reflectance for the six surfaces occurred only in the near infrared region (NIR). Average reflectance in the 700-1300 nm region accounted for 62% of the variation in the surface temperature based on all six surfaces (Fig. 4, $P<0.05$).

Surface temperature of artificial turfgrass components

Surface temperatures of artificial turfgrass components measured over a 10 hour period in October are plotted in Fig. 5 with air temperatures included for comparison. All surfaces (except air) revealed bell shaped curves, rising in temperature quickly in the morning hours and declining quickly in the early evening hours (the amplitude of the curve for bare soil was clearly lower than that of the other surfaces). All surface temperatures were higher than air temperature throughout the day, except for the last measurement period, just before sunset, when all surface temperatures were lower than air temperature.

Maximum surface temperatures occurred during the noon measurement period for five of the eight surfaces. However, maximum temperatures occurred around 14:00 hours for the green artificial turfgrass with black rubber beads, the green artificial turfgrass with no rubber beads and bare soil. No statistical

TABLE 1

Spectral reflectance in the Blue, Red, Near Infrared and Short Wave Infrared electromagnetic regions. Average spectral reflectance values plus standard deviations ( ) are reported for six different landscape surfaces measured at 1:00 pm on 26 August 2006.

Material	Blue (450-520 nm)	Green (521-600 nm)	Red (601-700 nm)	NIR (701-1300 nm)	SWIR (1301-2500 nm)
Artificial turf-green	0.027 (0.004)	0.049 (0.007)	0.032 (0.003)	0.072 (0.012)	0.068 (0.039)
Artificial turf-white	0.331 (0.005)	0.343 (0.002)	0.345 (0.001)	0.309 (0.031)	0.157 (0.084)
Asphalt	0.094 (0.001)	0.097 (0.001)	0.099 (0.000)	0.099 (0.001)	0.105 (0.033)
Concrete	0.357 (0.009)	0.394 (0.011)	0.409 (0.001)	0.393 (0.008)	0.425 (0.041)
Turfgrass	0.046 (0.007)	0.087 (0.009)	0.064 (0.009)	0.559 (0.091)	0.200 (0.125)
Dry soil	0.210 (0.014)	0.277 (0.026)	0.352 (0.019)	0.508 (0.058)	0.559 (0.070)

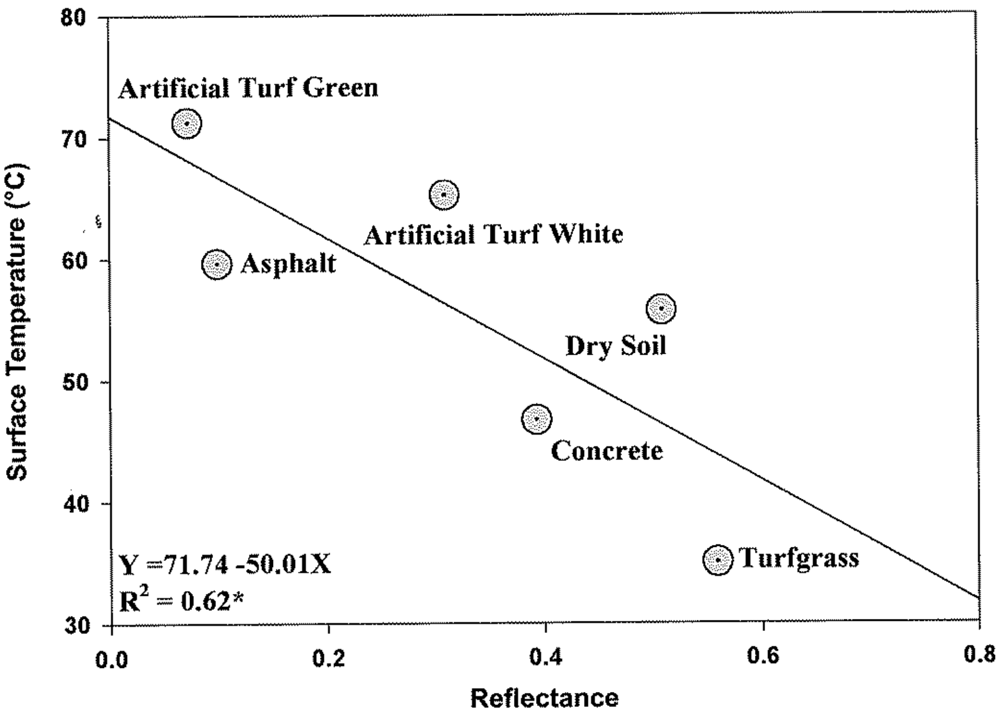

FIGURE 4. Temperature as a function of average reflectance in the NIR region (700-1300 nm) for 6 different surfaces.

difference ($P>0.05$) was observed between the artificial turfgrass cuttings placed in a stacked horizontal fashion and vertical intact artificial turfgrass without rubber beads. However, adding rubber beads whether black or white increased the temperature of the artificial turfgrass system. The highest surface temperature of 51.2°C (124°F) recorded during the 10 hour period was on green artificial turfgrass with black rubber beads. Although white rubber beads were 9.1°C cooler than black rubber beads at 12:00 hours, the maximum surface temperature of artificial turfgrass with white rubber beads was only 5.3°C lower than artificial turfgrass with black rubber beads with statistical differences only during the mid day period ($P<0.05$). Because the beads were only coated, we do not know if solid white rubber might have less heat absorption and retention than coated rubber beads.

Temperature differences between 08:00 hours and the maximum midday value were greatest for the green artificial turfgrass with black rubber beads, followed by the artificial turfgrass matting, black rubber beads, and green artificial turfgrass with white rubber beads (ranging from 25.4°C to 29.7°C).

Energy balance and heat transport through artificial turfgrass

Energy balance components (Rn, H, G) for the artificial turfgrass in the experimental plot are shown in Fig. 6A for a representative 7 day period covering 7-14 September 2006 (data were visually obscured when the entire period was included). Net radiation peaked

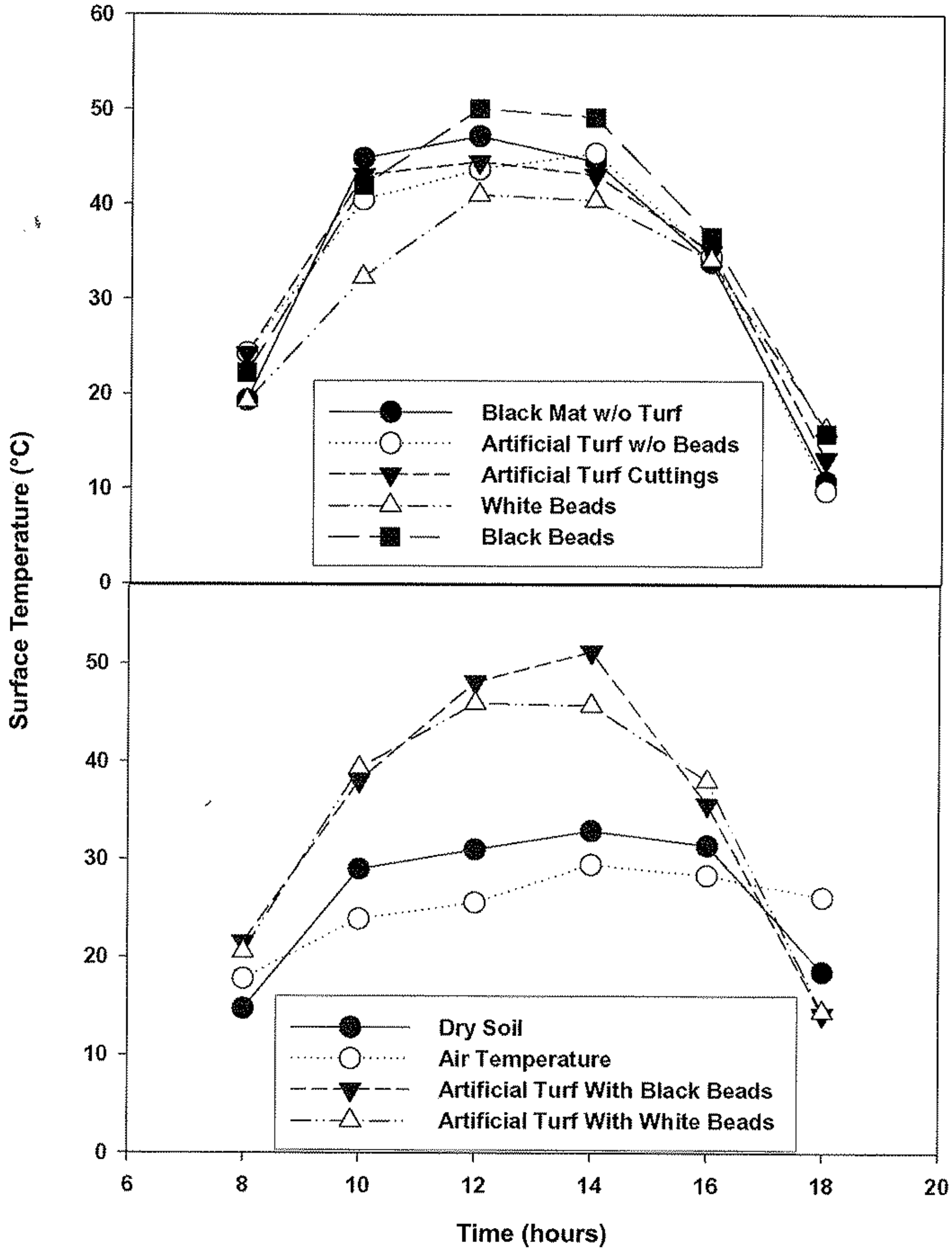

FIGURE 5. Temperatures of five different artificial turfgrass components (A) and different surfaces over a 10 hour period on 12 October 2006.

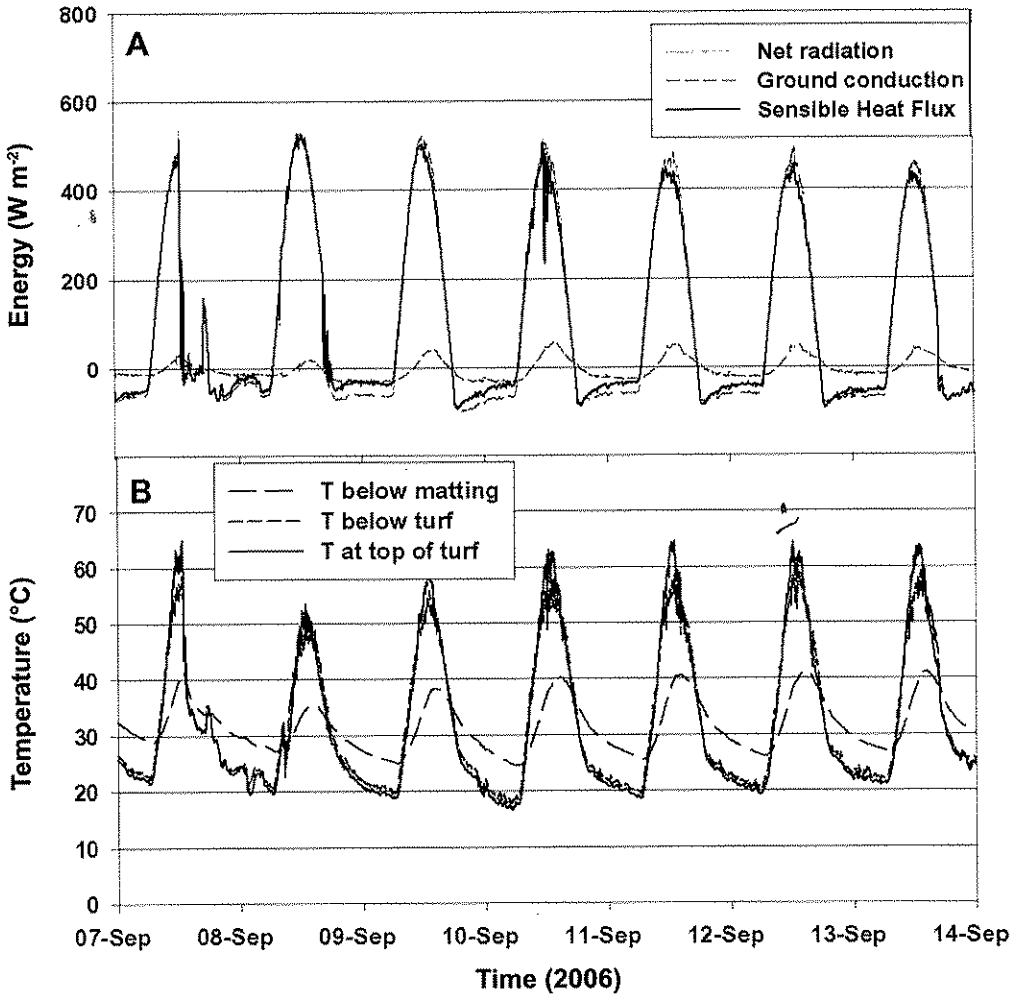

FIGURE 6. Net radiation and soil heat flux (A) and temperatures (B) above and below artificial turfgrass matting for 7 days of the 40 day monitoring period.

during mid day, with values close to 500 W m^{-2} for the days shown. The plots show that the majority of net radiation (>90%) was lost to the atmosphere as sensible heat flux. Less than 10% of energy striking the turf surface was conducted below the turf material and into the soil. These results confirm those shown in Fig. 1. Here, because of the very small ground conduction and the negligible latent heat flux (from evapotranspiration of water), a rapid rise in Rn resulted in increased sensible heat and surface temperatures. Moreover, Fig. 6B shows the temperature time series using the thermocouples for the same monitoring period. Although temperatures at the top of the grass blades were also measured, temperatures below the rubber beads were about 6% higher on average than the temperature at the top of the blades (Temperature below beads = 1.061*Temperature top of blades + 1.993, r^2=0.97, P<0.001 for the entire 40 day monitoring period). Peak temperatures averaged 18.8 °C (±5.1°C) higher within the black rubber beads versus below the matting (P<0.05). Temperatures above the matting peaked between 12:00 and 13:00 whereas temperatures below the matting peaked closer to 15:00, illustrating the relatively small thermal conductivity of the turf matting. Hourly net radiation (Rn) values (night and day) accounted for 75% (P<0.001) of the variability in the hourly temperatures of the artificial turfgrass (within black rubber beads). Although we did not measure hourly air temperatures above the test plot, hourly air temperatures as reflected by the thermocouple within the data logger, accounted for less variation in the surface temperature of artificial turfgrass than was accounted for by Rn (r^2=0.64, P<0.001).

DISCUSSION

Artificial turfgrass represents a viable alternative to natural turfgrass, especially when considering the potential water savings associated with the elimination of all irrigation. For example, irrigation of bermudagrass in Las Vegas, NV has been reported to be greater than 18,300 m^3 per ha per year (6 acre feet per acre) (Devitt *et al.* 1992). However, the temperature of the artificial turfgrass material was shown to react very quickly to changes in radiation, much more quickly than any other surface measured during our study. We measured surface temperatures of artificial turfgrass as high as 76°C, and these values did not represent turfgrass response during the two hottest months of the year (June and July). The values reported here are similar to those reported by Brakeman (2005). Moreover, Williams & Pulley (2006) also measured elevated temperatures on synthetic surfaces and indicated that the Safety office at Brigham Young University set a safe surface temperature of 50°C, stating that injury to the skin can occur within 10 minutes of exposure to artificial turfgrass with temperatures ≥50°C, jeopardizing the safety of those who play on the surface. Based on a 50°C threshold value, the artificial turfgrass system exceeded this value for 9 hours during a day in late August and for approximately 2 hours during a day in mid October. This would suggest that surface temperatures during summer months (June-August) could preclude the recreational use of artificial turfgrass during the majority of daytime hours. This would clearly offset, to some extent, the benefits achieved with reduced irrigation.

Our results contradict those of Buskirk *et al.* (1971) who suggested that one should not assume a lower heat rise on hazy or cloudy days. We measured large changes in surface temperature of artificial turfgrass associated with changes in solar radiation and cloud cover. However, the ratio of the surface temperature in °C to the solar radiation in Wm^{-2} was very stable during mid day and when no cloud cover occurred. October and March had very similar values, but a separation occurred with the August data (Fig. 7, P<0.05). It should be noted that even a wider separation in the data occurred with the living turfgrass. These differences in surface temperature to solar radiation ratios are due to the zenith angle of the sun. October and March measurement periods were very close to the fall and spring equinox, when the zenith angle is higher compared to August. The solar zenith angle can be used to calculate the vertical component of direct sunlight shining on a horizontal surface. For Las Vegas, the solar zenith angles are approximately 36 degrees for the spring equinox and 13 degrees for the summer solstice. These zenith angles would correspond to an approximate vertical component of direct sunlight of 81% versus 97% (spring vs. summer).

Because the artificial turfgrass has an apparent low specific heat, energy loading will

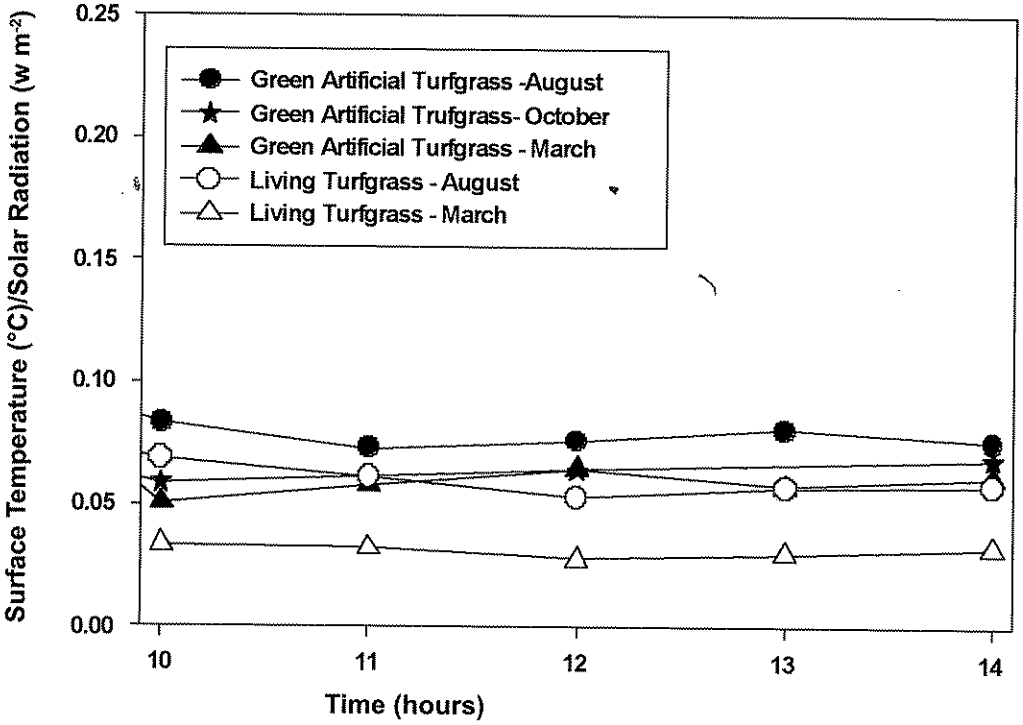

FIGURE 7. Response of artificial turfgrass and living turfgrass to solar radiation for monitoring periods in August, October and March.

lead to a consistent rise in temperature, with the resulting surface temperature driven by the total amount of solar radiation occurring at a given time. In contrast, the temperature of living turfgrass was consistently below air temperature and all other surfaces. This would suggest that the specific heat of the living turfgrass is high relative to the other surfaces in this study. Living turfgrass often has 70% moisture by weight (Brown *et al.* 2004). Water has a very high specific heat (4.186 J g^{-1} K^{-1}) and energy is absorbed when water moves from liquid to vapor during the process of transpiration. Asphalt, concrete and soil all have fairly low specific heats (0.92, 0.88, and 0.80 J g^{-1} K^{-1}, respectively,). However, the soil and concrete in our study were lighter in color than the black asphalt contributing to contrasting reflective properties.

We measured spectral reflectance over the 350 to 2500 nm range and reported spectral curves for the six different surfaces. The shape of the spectral curves, especially the amplitude at different wavelengths provides insight into how different materials handle energy loading. In our study, green artificial turfgrass maintained the lowest reflectance over the entire spectrum and hence experienced the highest temperatures. Average reflectance for green artificial turfgrass over the entire energy spectrum was 5.7 ± 0.2%, lower than black asphalt, which averaged 9.8 ± 0.6%. The spectral curves for green artificial turfgrass and asphalt contrasted with the other surfaces including natural turfgrass. Healthy green vegetation absorbs large amounts of energy in the blue and red regions of the spectrum (low reflectance) due to chlorophyll/pigments and reflects large amounts of energy in the near infrared region, due to the internal cellular structure of the leaves (Thenkabail *et al.* 2000). Our results would clearly indicate that the amount of reflectance in the 700-1300 nm range will be correlated with surface temperature, suggesting that manufacturers should investigate how to alter artificial turfgrass components to increase reflectance in this part of the energy spectrum. It is worth noting that NASA currently maintains spectra for over 2000 natural and man-made products (http://speclib.nasa.gov 2007). The spectra obtained for asphalt, concrete, soil and turfgrass in our study were very similar to those found in the NASA spectra library. Unfortunately, spectra for artificial turfgrass were not available in the library.

We conclude that most of the energy from the sun went into heating the plastic blades of turfgrass and black rubber beads, with little transfer of heat into the fill material below the matting. Because of a low apparent specific heat, the artificial turfgrass demonstrated a rapid rise and fall in temperature based on time of day and cloud cover. We also note that results reported here might differ with different types of artificial turfgrass. McNitt (2006) reported temperature variations as much as 10°C (18°F) during two different monitoring periods on ten different artificial turfgrass products, which would indicate that the reflection and absorption of energy varies based on product material and construction. Therefore, managers of recreational fields should investigate all available products prior to any purchase and should consider a more reflective color, the use of white rubber beads and locating recreational fields in areas of greater shade. Excellent empirical relationships existed in our study between solar radiation and surface temperatures, suggesting that solar radiation could be used as a way of managing when recreational fields can be safely used.

The results in this study showed that the intensity of solar radiation striking the artificial turfgrass and the solar zenith angle were primarily responsible for elevating the artificial turfgrass temperature. The temperature rise of the artificial turfgrass was exacerbated by the very low reflectance in the 700 to 1300 nm range. These physical characteristics of light are, of course, not isolated to warm cities like Las Vegas, NV, but rather are present in all cities, including those in more temperate climates (US, Europe and Asia). Therefore, even cities with cooler air temperatures might need to address the potential risks associated with elevated surface temperatures of artificial turfgrass. Although the magnitude of the temperature rise and the duration may be less than noted in our study, surface temperatures approaching or exceeding 50°C would be possible.

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