EFFECTS OF LANDSCAPE SURFACE MULCHES ON DESERT LANDSCAPE MICROCLIMATES AND RESPONSES OF THREE SOUTHWEST DESERT PLANTS TO LANDSCAPE SURFACE MULCHES AND DRIP IRRIGATION

by

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ABSTRACT

Effects of three landscape surface mulches, shredded landscape tree trimmings, ponderosa pine residue and decomposing granite, and turf on desert landscape microclimates and characterization of responses of three southwest desert plants, *Encelia farinosa*, *Atriplex canescens* and *Opuntia santa rita* to a combination of landscape mulch and drip irrigation rate treatments were evaluated over two years. Daytime soil temperatures were generally lower under the two organic surface mulches and turf than under decomposing granite or in soil with no landscape surface mulch cover. Organic mulches had higher daytime and lower nighttime surface temperatures than either decomposing granite or bare soil; however, turf consistently had the lowest surface temperatures. Daytime net radiation was most positive over turf during both years. Nighttime net radiation was most negative over landscape surfaces covered with decomposing granite or with no surface mulch cover. Soils without surface mulch or covered with organic mulch had the greatest and least diel soil heat flux, respectively. Soils beneath mulches evaporated less soil water than bare soil. All *Encelia* and *Atriplex* shrubs were either drip irrigated with 2550 L or 1275 L of water per year or not irrigated after transplanting (control treatment). Landscape mulches had no affect on growth of *Atriplex* or *Encelia* shrubs. Final shoot dry mass was greatest for *Atriplex* and *Encelia* shrubs that were not irrigated. *Atriplex* had no mortality. In contrast, *Encelia* shrubs grown in plots with either organic mulch or no mulch had about 40% and 13% mortality, respectively. *Encelia* shrubs grown in plots with decomposing granite mulch had no mortality. For both years, *Opuntia* cacti grown in plots with shredded landscape tree trimmings had higher padded stem relative water content than those grown in plots without mulch. In a hot, desert climate landscape tree trimming and ponderosa pine residue mulches were more effective at moderating soil heat gain and water loss than decomposing granite mulch. In addition, these findings suggest that supplemental drip irrigation might not be needed to grow some southwest desert shrubs in local urban landscapes, and desert shrub response to mulches is taxa specific.

Dedicated to my parents:

Dr. Kenneth William Karren, Sr. and

Anne Louise Henderson Karren

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LIST OF ABBREVIATIONS

Abbreviation	Meaning
BS	bare soil
C	conductive heat transfer
d	mulch layer thickness
DM	dry mass
DG	decomposing granite
FM	fresh mass
G	soil heat flux
GI	growth index
G_m	heat flux through mulch
k_m	mulch thermal conductivity
k_s	soil thermal conductivity
LTT	landscape tree trimmings
PPR	ponderosa pine residue
RWC	relative water content
SM	saturated mass
T_{soil}	temperature of soil surface beneath mulch
$T_{soil5cm}$	temperature of soil at 5-cm depth
$T_{soil30cm}$	temperature of soil at 30-cm depth
$T_{surface}$	temperature of landscape surface
VWC	volumetric water content

CHAPTER 1

REVIEW OF LITERATURE

The word “mulch” is possibly derived from the Anglo-Saxon word “melsc” or the German word “molsch” meaning mellow, soft or rotten (Borland, 1990). Mulch is defined as any material placed on the soil to cover and protect it (Harris et al, 2004) and can be broadly categorized into two main categories: organic and inorganic. Common inorganic mulches include crushed rock or stone, black or colored polyethylene and other landscape fabrics, or even recycled chipped tires. Organic mulches may be comprised of various plant residue, including tree bark, wood chips, leaves, conifer and pine needles, lawn clippings, straw, corn cobs, coconut coir, peanut and cocoa hulls, green waste compost or recycled newspaper. The horticultural practice of using inorganic and organic surface mulches may offer several beneficial effects to the urban landscape including moderating soil temperatures, altering landscape patterns of heat transfer, reducing soil water evaporation, adding organic matter to the soil system, reducing weed colonization and preventing soil erosion.

Effects of surface mulches on soil temperature. Inorganic and organic mulches influence landscape soil temperatures. Some gravel-sand mulches may increase soil temperatures. For example, in loess soil in northwest China, gravel-sand mulch can increase soil temperature 0.5 to 4.5°C at a depth of 10 cm (Li, 2003). In contrast, Iles and Dossman found that soil temperatures below five inorganic mineral mulches were on average 3.4°C lower than bare soil controls

(1999). Organic mulches are extremely efficient at moderating landscape soil temperatures and may lower summer soil temperatures an average of 5.9°C (Iles and Dossman, 1999). Pickering et al found that green waste compost and conifer bark chips can reduce summer soil surface temperature approx. 5°C compared to bare soil (1998). Inorganic and organic mulches differentially affect landscape soil temperatures. Studies comparing organic and inorganic mulches have shown that soil temperatures below organic mulches are generally lower and have decreased diurnal amplitude than below inorganic mulches (Ashworth and Harrison, 1983, Holloway, 1992, Skroch et al, 1992, Iles and Dossmann, 1999, Montague and Kjelgren, 2004)

Effects of surface mulches on landscape heat transfer. Because mulches generally have higher albedo than bare soil and act as an insulating barrier to conductive and convective solar radiant heat transfer, mulches alter landscape surface energy balance and heat transfer to the soil. Li (2003) reported higher heat transfer into gravel-sand mulched soils than bare soil control, attributed to the mulch's small heat storage capacity, which resulted in an increase in temperature for the mulch layer and in heat transmission to the soil below. Montague et al (2000) found that summer soil heat flux was about 70 W/m^2 lower below bark mulch than below turf grass and in subsequent studies (Montague and Kjelgren, 2004) reported that, for six common landscape surfaces, longwave radiation flux was greatest over pine bark mulch and least over turf. van Donk and Tollner (2000, 2001) have created mathematical models to predict thermal conductivity values for some inorganic and organic mulches.

Effects of surface mulches on soil moisture. Inorganic mulches, like organic can reduce soil water evaporation rates (Smith and Rakow, 1992, Kraus, 1998). Soil water retention in mulched soils, however, is specific to mulch type. Iles and Dossman (1999) found higher soil moisture levels below shredded bark, wood chip, screened pine and pea gravel mulches compared to crushed brick, carmel, river and lava rock mulches. Li (2003) showed that water infiltrates to depths of 60 cm in a loess soil under gravel-sand mulch compared to only 10 cm in a bare plot and soil moisture content was higher and evaporation rates lower in gravel-sand mulched plots than in bare soil control plots. For soils with a given soil water content, a rock fragment mulch reduces evaporation significantly (van Wesemael et al, 1996). In a study comparing soil moisture between green waste compost mulch and conifer bark chip mulch, significantly higher soil moisture content was observed under green waste compost (Pickering et al, 1998). In this same experiment, control treatments had significantly lower soil moisture levels than all other mulch treatments; furthermore, the deeper the mulch treatment, the greater the moisture retention beneath. As well as conserving moisture in field soils, use of pine bark or sphagnum moss mulch decreases the need for frequent irrigation, thus improving water use efficiency in young impatiens plants in containers (Lohr & Pearson-Mims, 2001). Mulch can also inhibit water from penetrating landscape soil. If rainfall is light, for example, organic mulches may impede water penetration to the soil, such as in arid, desert regions (Harris et al, 2004).

Effects of surface mulches on soil structure and nutrient availability. Application of mulch to the soil surface using crop residues, green waste or plant litter adds organic matter, encourages earthworm activity and protects soil aggregates from rainfall and direct sunlight (Brady & Weil, 2002). The decomposition of organic mulches enhances soil aggregate stability, increases infiltration of rain or irrigation water, and increases soil biodiversity (Brady & Weil, 2002). Addition of organic matter to the soil system also enhances soil structure, which in turn helps prevent soil compaction (Brady & Weil, 2002). Incorporation of organic matter to the soil system may increase plant available nutrients; however, some organic mulches such as pine bark residue degrade too slowly to add any appreciable organic matter to the soil. Logyard residue, for example, is a mixture of soil, rock, bark, and fine organic matter produced in large quantities by forest products companies. This residue is periodically scraped up and transported to landfills because it cannot be used as a boiler fuel and its high organic content restricts its use as fill (Campbell & Tripepi, 1992). Sawdust, wood chips and bark from the lumber industry have long been sources of mulches and soil amendments, especially for landscape use. Because these wastes are high in lignin and have very wide C/N ratios, they do no readily decompose to supply plant available nutrients in the soil (Brady & Weil, 2002). Furthermore, soil amended with sawdust to improve the soil structure may actually cause plants to become nitrogen deficient and require an additional application of nitrogen (Brady & Weil, 2002). A co-application of a nitrogen fertilizer along with organic mulch is generally recommended due to the theory that microorganisms that degrade and decompose mulch sequester the nitrogen as they consume it (Borland, 1990). Such nitrogen immobilization would be temporary, however, because once about half the organic matter has decomposed the microorganism populations start to decline and release any sequestered nitrogen back into the soil (Borland, 1990). Current research indicates that mulching can increase nitrogen uptake by plants. In an experiment to determine the effects of black polyethylene mulch on the water use efficiency and macro-nutrition of bell pepper, Kirnak et al (2003) found that mulching mitigates the negative effects of water stress (decreased leaf nitrogen and magnesium) on plant growth in semiarid conditions and also increases nitrogen availability to the plants. Furthermore, geranium crops grown using paddy straw mulch increased nitrogen uptake by 33% and 28.4% (in two annually consecutive experiments) over the non-mulched control (Ram & Roy, 2003). The decomposition rate of mulches with high nitrogen content also depends on the indigenous microflora present. Research on grass mulch plant residues reveals that such microflora determines both the rate of decomposition of the surface-applied grass mulch and the N-mineralization and denitrification of the surface mulch (Flessa et al, 2002).

Effects of surface mulches on landscape tree and shrub growth. Use of surface mulches may improve the appearance of some landscape plants (Harris et al, 2004). However, landscape plant growth response to application of surface mulches appears to be taxa and mulch type specific. Organic mulches such as leaves, pine nuggets, pine straw, grass clippings, and chipped limbs have been shown to increase young pecan tree trunk cross-sectional area 1.75-fold compared to unmulched trees (Foshee et al, 1996). In addition, Smith et al (2000) found that a 30-cm layer of wood chip mulch applied around pecan trees substantially increased tree growth. Fairview Flame® red maple trees grown in inorganic mulches had larger stem calipers than those growing in shredded bark mulch (Iles and Dossman, 1999). In an arid environment, however, organic mulches may not increase the overall growth of plants. Pine bark mulch treatments of 7.5-cm and 15-cm depth had no effect on the crown growth of five native southwest shrubs (cliffrose, curlleaf mahogany, desert olive, Apache plume, and winterfat) compared to the control treatment (Hild & Morgan, 1993).

Effects of surface mulches on weed reduction and erosion control. Other benefits of mulch include reducing weed growth and providing erosion control. A study by Teasdale and Mohler (2000) showed that weed emergence declines with increasing depth of mulch mass. Skroch et al (1992) found that organic mulches reduced total weed counts by 50% compared to bare soil and additional use of polyethylene fabric resulted in complete weed control. Holloway (1992) similarly found weed control was greatest for wood chip mulches compared to stone mulches. Smith et al (1997) showed that recycled paper mulch provides weed control as well as standard landscape surface mulch treatments. Although not aesthetically appealing, inorganic mulches like black polyethylene, woven polypropylene and heavy-duty green plastic work best for weed control because they do not decompose as fast as organic mulches (Ashworth & Harrison, 1983). Current horticultural practices, however, generally favor use of landscape surface mulches mulch in concert with application of pre- and post-emergent herbicides over use of unsightly landscape fabrics.

Mulch may also be useful in erosion control. Mulch application increases water infiltration into the soil profile by preventing a soil crust from forming and consequently reduces overland runoff (Brady & Weil, 2002). In northwest China the use of gravel-sand mulches has been used in agriculture for hundreds of years (Li, 2003). The loess soils of this region of China are susceptible to high losses due to wind and water erosion. Experiments with different depths of gravel-sand mulch in wind tunnels demonstrated that wind erosion rate decreases with increasing pebble cover densities, suggesting that this type of mulch is effective in controlling wind erosion (Li, 2003).

Use of inorganic and organic surface mulches offer several potentially beneficial effects to urban landscape including moderating soil temperatures, altering landscape patterns of heat transfer, reducing soil water evaporation, adding organic matter to the soil system, reducing weed colonization and preventing soil erosion. In addition, surface mulches may provide aesthetic benefits for landscapes, and many municipalities in the southwest United States ordinate application of surface mulch to all bare soil surfaces for dust abatement. Not all effects of mulches in the landscape are positive: there are toxicity problems associated with surface mulches. With the application of organic mulches comes the risk of toxic tissues in the surface mulch interfering with growth of landscape plants. Some toxic tissues include: eucalyptus sawdust and leaves, red-wood and cedar sawdust, Douglas fir, larch and spruce bark, and mulch that has been improperly composted, which can have elevated concentrations of methane, alcohol, ammonia gas or hydrogen sulfide gas (Harris et al, 2004). When placed around plants, symptoms of marginal leaf chlorosis, leaf scorch, defoliation and death may occur (Svenson and Witte, 1989). In addition, little is known, however, about the effects of organic surface mulches on landscape thermal processes in the hot, desert climates typical of cities like Phoenix, Arizona and the effects organic surface mulches on indigenous desert landscape plants.

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CHAPTER 2

EFFECTS OF SURFACE MULCHES AND TURF ON DESERT LANDSCAPE MICROCLIMATES

Abstract. Effects of three landscape surface mulches, shredded landscape tree trimmings, ponderosa pine residue and decomposing granite, and turf on desert landscape microclimates were evaluated over two years (2004 and 2005). Daytime soil temperatures at 5- and 30-cm depths were generally lower under the two organic surface mulches and turf than under decomposing granite or in soil with no landscape surface mulch cover. Organic mulches had higher daytime and lower nighttime surface temperatures than either decomposing granite or soil with no surface mulch cover; however, turf consistently had the lowest surface temperatures. Daytime net radiation was most positive over turf grass during both years. Nighttime net radiation was most negative over landscape surfaces covered with decomposing granite or with no surface mulch cover. Soils without surface mulch or covered with organic mulch had the greatest and least diel soil heat flux, respectively. Soils beneath mulches evaporated less soil water than bare soil. In a hot, desert climate landscape tree trimming and ponderosa pine residue mulches were more effective at moderating soil heat gain and water loss than decomposing granite mulch.

Introduction

Landscape surface mulches moderate soil temperatures, decrease soil water evaporation, and increase water infiltration (Brady and Weil, 2002; Harris et al, 2004). Surface mulches can be derived from inorganic or organic materials; however, inorganic and organic mulches can differentially affect thermal processes in the landscape. Iles and Dossmann (1999) showed that soil temperatures below organic mulch treatments at a 10-cm depth were on average 2.5°C lower than soil treated with inorganic mineral mulches. Surface mulches can also alter radiant heat transfer and modify landscape surface energy balances (van Donk and Tollner, 2001; Montague and Kjelgren, 2004). Montague et al (2000) reported that soil heat flux was up to 70 W/m^2 lower beneath pine bark mulch than turf and later showed that longwave radiation flux was greater over pine bark mulch compared to several inorganic mulches, impervious surfaces and turf (Montague and Kjelgren, 2004).

Soil water evaporation is an important component of landscape surface energy balance. Inorganic and organic landscape surface mulches have both been shown to reduce soil evaporation rates (Li, 2003; Kraus, 1998; Pickering et al, 1998; Ashworth and Harrison, 1983). Rock fragment mulches have been shown to reduce cummulative evaporative soil water loss as much as 10-mm after 7 days, depending on soil type (van Wesemael et al, 1996) and gravel-sand mulches in the loess region of China have been found to reduce cummulative soil water evaporation about 10-mm after 14 days (Li, 2003).

In the Southwest United States, municipal promotion of landscape water conservation has resulted in an overall decline in the use of turf as a landscape surface cover (Martin, 2001). Additionally, federal mandates by the Environmental Protection Agency (EPA) that regulate urban concentrations of atmospheric particulates such as dust, have caused many southwest municipalities to impose dust abatement ordinances which require the covering of all non-vegetated landscape surfaces with a mulch material. In major cities such as Phoenix, Tucson, Albuquerque and Las Vegas, the prevalent landscape surface mulches are crushed stone and pumice, pebbles, and decomposing granite. The capacity of these inorganic mulch materials and others to ameliorate temperature fluctuations within the root zone of landscape plants is a direct function of their thermal properties.

Waste disposal is a critical problem facing cities across the United States (Campbell & Tripepi, 1992; Glenn et al, 2000; Smith et al, 1997). In 1989, the EPA mandated a 25% reduction in landfill disposal by 1995 and a total reduction of 75% by the start of the 21st century (Smith et al, 1997). Each year the landscape industry in the Southwest generates copious amounts of yard waste such as tree and shrub trimmings that are typically disposed of in public land fills. Recently, researchers reported that as much as 35% to 80% of annual above-ground net primary production of southwest landscape trees and shrubs is removed as prunage (Stabler, 2003).

On the Mogollon Rim, a 2500-m plateau that transects north and central Arizona and part of western New Mexico, is the largest contiguous ponderosa pine forest in the world. Ponderosa pine timber harvests within this region have created extensive stockpiles of log yard residue despite its use by the nursery industry as a container substrate constituent. The relatively high C:N ratio (150:1) of uncomposted log yard residue restricts its disposal into public landfill sites (Campbell & Tripepi, 1992), and stockpiles of composting log yard residue can cause environmental problems due to spontaneous combustion (Campbell & Tripepi, 1992).

Use of shredded landscape trimmings and composted pine residue as a landscape surface mulch might be a viable alternative to their disposal in public landfills. Though use of organic materials as surface mulch is common in mesic and temperate climates, they are rarely used in southwest landscapes despite increased product availability because of concerns about surface aridity and mulch stability. Moreover, research is lacking on how organic mulches affect landscape surface energy balances, soil temperatures and soil water evaporation rates in hot, desert climates. The purpose of this research was to compare the effects of organic and inorganic landscape surface mulches and turf on desert landscape microclimates.

Materials and Methods

Research was conducted during 2004 and 2005 to determine the effects of three surface mulches and evergreen turf on desert landscape microclimates. The three landscape surface mulches were shredded urban landscape tree trimmings (LTT) donated by DLC Resources (Phoenix, AZ), composted ponderosa pine residue (PPR) donated by Southwest Forest Products (Phoenix, AZ) and Red Mountain Coral decomposing granite (DG) quarried locally from the Salt River drainage. Table 2.1 shows the physical characteristics of the three landscape surface mulches.

Several experiments were accomplished at sites within the Phoenix metropolitan region on the northeast edge of the Sonoran Desert in the southwest United States. The hot, desert climate of Phoenix is characterized by intense radiation and extreme heat from May through September. Summer daytime maximum temperatures regularly exceed 40°C. Precipitation is normally distributed bimodally during winter and summer. Spring and fall seasons are normally dry. Total rainfall and potential evapotranspiration during April 2004 to October 2005 were 499-mm and 3371-mm, respectively (http://ag.arizona.edu/azmet/).

One experiment was conducted to determine the effects of three landscape surface mulches on soil thermal flux properties at a landscape research site established and previously described by Stabler (2003). The research site consisted of 14, 9-m x 9-m plots that had been previously planted in

May 1999 with a mixture of landscape trees and shrubs (Stabler, 2003). During April 2004, all surface debris was removed from each plot and three landscape surface mulches, LTT, PPR, or DG were each applied randomly to four of the plots at a minimum depth of 5 cm, which is the minimum depth stipulated by the Arizona Department of Transportation Landscape and Irrigation Specifications, Section 430.4. The remaining two landscape plots did not receive any surface mulch and were considered bare soil (BS) controls. The thickness of the landscape surface mulch layer was recorded at the beginning and end of the experiment by making 12 measurements of mulch depth per plot in three north-south transect gradients. Soil at the landscape plots was a Rillito series gravelly loam (taxonomic class = Coarse-loamy, mixed, superactive, hyperthermic Typic Haplocalcid, bulk density = 1.57 g/cm^3) with a 0 to 1 percent slope. Soil moisture at each of the plots ranged from an average of 20% volumetric water content after the 2005 winter rainy season to an average of 6% volumetric water content during the hot, dry summer months (data collected using a Field Scout TDR 100 Soil Moisture System, Spectrum Technologies, Plainfield, IL).

During 2004 and 2005, diel patterns of total irradiance (W/m^2), net radiation (W/m^2), mulch and soil surface temperatures, and soil temperatures at two soil depths (5- and 30-cm) were recorded under clear sky conditions. Diel patterns of total irradiance, net radiation, and mulch and soil surface temperatures were recorded seasonally (spring, summer and fall), and soil temperatures were recorded continuously. Total irradiance was recorded with a

LI200S pyranometer (LI COR Biosciences, Lincoln, NE) that was placed on top of the mulch surface at the center of each mulch plot. Net radiation was recorded with a Q7_1-L REBS net radiometer (Campbell Scientific, Logan, UT) horizontally positioned at the center of each plot at a height of 90-cm above the mulch surface. Soil surface temperatures under the LTT, PPR, and DG mulch treatments were recorded seasonally with copper-constantan thermocouples. Total irradiance, net radiation and soil surface temperatures under the mulch were recorded every 300-sec and averaged for 15-min intervals using a 21X micrologger (Campbell Scientific, Logan, UT). For total irradiance and net radiation, an additional single integrated value was calculated for every 6-hr of data collected. Mulch and bare soil surface temperatures were recorded every 4-hr with a hand held Oakton InfraPro Infrared Thermometer (emissivity = 0.94, 7° field of view, Oakton Instruments, Vernon Hills, IL,) at about 30-cm above the mulch surface. Model 100 WatchDog data loggers (Spectrum Technologies, Plainfield, IL) positioned at 5- and 30-cm depths near the center of each plot were used to record soil temperatures. The WatchDog data loggers were programmed to record temperatures every two hours from January 2004 to November 2005.

In another experiment, two 9-m x 9-m plots were established during June 2004 on the turf of the parade grounds (approx. 1 Ha) at the Arizona State Polytechnic campus in Mesa, Arizona. The turf was an evergreen mixture of warm season hybrid Bermuda (*Cynodon dactylon* (L.) Pers.) overseeded during the fall with cool season perennial rye (*Lolium perenne* L.). The entire turf area was sprinkler-irrigated nightly throughout the year and mowed weekly to an average height of 5-cm. Seasonal (spring, summer and fall) net radiation, total irradiance, turf surface temperatures, thatch temperatures and soil temperatures at 5- and 30-cm depths were recorded in the same manner and iterations as described in the previous experiment.

Another set of experiments was conducted to determine mulch bulk density, thermal conductivity and albedo. Bulk density (g/cm^3) was calculated as the weight of oven dry mulch, dried for 72 hours at 105°C, divided by the volume occupied by that mulch for five separate samples. Thermal conductivity (W/m°C) was determined by recording heat flux through the mulch and soil and mulch surface temperatures for each mulch type in three 45-cm x 60-cm Styrofoam containers each containing a 5-cm layer of soil covered with 5-cm of mulch. Soil heat flux plates (HFT3 Soil Heat Flux Plate, Campbell Scientific, Logan, UT) and copper-constantan thermocouples were placed beneath the mulch in the center of each box (protocol adapted from field mulch thermal conductivity studies Montague and Kjelgren, 2004). Mulch surface temperatures in each box were recorded with a hand held Oakton InfraPro Infrared Thermometer (Oakton Instruments, Vernon Hills, IL), emissivity set at 0.94, with a 7° field of view and positioned approx. 2-cm above the measurement surface. For measurements, boxes were placed in a greenhouse maintaining 38°C ambient daytime temperature and allowed to acclimate for 72 hours. Heat flux measurements and soil surface temperatures were taken every 10-sec, averaged and uploaded into Model 23X Micrologger (Campbell Scientific, Logan, UT) and recorded every 5 minutes for 30 minutes to determine mulch thermal conductivity. Mean total irradiance, recorded every 5-min with a LI200S pyranometer (LI COR Biosciences, Lincoln, NE) placed next to the boxes, was 814 W/m^2 during the experiment. Mulch albedo was determined at the end of the first growing season and for freshly laid landscape tree trimmings and ponderosa pine residue at the previously described landscape mulch experiment. Total irradiance was recorded with a LI200S pyranometer (LI COR Biosciences, Lincoln, NE) attached to a stick approximately one meter in length. Below the pyranometer a toothpick attached to the stick was used to determine the incident sun angle. Incoming all-wave radiation and reflected all-wave radiation (mV DC) were recorded and the ratio of the two was calculated as mulch surface albedo.

Another experiment was conducted for 22 days (31 May to 21 June 2005) at an open, graded field site on the Polytechnic campus of Arizona State University (Mesa, AZ) to compare evaporative water loss and moisture content of soil covered by the three landscape surface mulch treatments previously described. Bare soil was used as a fourth control treatment. During this study mean ambient diel air temperatures ranged from a minimum of 19°C to a maximum of 45°C with a mean of 31°C; total daytime irradiance ranged from a minimum of 0.074 W/m^2 to a maximum of 1203 W/m^2 with a mean of 546 W/m^2; there was no rainfall during this experiment (data courtesy of the Arizona State

University Polytechnic Photovoltaic Testing Laboratory, Mesa, AZ). Total potential evapotranspiration during this experiment was 167-mm (http://ag.arizona.edu/azmet/).

Sixteen, open-top polyvinyl chloride (PVC) cylinders (30-cm long x 15-cm diameter) with solid PVC bottoms were constructed to measure soil water evaporation and moisture content. At the bottom of each cylinder, nine, 6-mm holes were drilled in a uniform pattern to allow water drainage. Plastic mesh screens were inserted at the bottom of each cylinder to prevent loss of soil. Each cylinder was filled with 7.5-kg (~25-cm depth) of air dried, sieved (5-mm screen), and uniformly mixed Rillito series gravelly loam soil (bulk density = 1.57 kg/m^3) plus a 5-cm layer of each mulch type on top of the soil, except for the bare soil control cylinders, which were filled with 9-kg of soil only (~30-cm depth).

Sixteen square plots (0.58 m^2/plot) were established in a four by four grid arrangement within a 100 m^2 area at an open field site that was graded and leveled. The plots were equidistant from each other and separated by a 1-m buffer of bare soil. Around the perimeter of each plot was a wood border embedded in the soil such that 5-cm of the wood border was above the plot surface grade. On May 31, 2005, the soil-filled PVC cylinders were placed vertically into the soil at the center of each plot so that the surface grade within each PVC cylinder and surrounding plot was the same. Next, a 5-cm layer of one of the three surface mulch treatments or bare soil (control treatment) was applied onto the surface of each plot including the surface of each PVC cylinder, except the bare soil control cylinders. The soil-filled PVC cylinders with surface mulch covers remained in place for five days to acclimatize to field conditions.

After five days, the PVC cylinders were removed from the plots and 1.7-kg (1.8-kg in bare soil cylinders) of distilled water (25^{o}C) was added in small increments to the soil beneath the mulch in each cylinder and allowed to percolate slowly through the soil profile until water was draining from the bottom. A preliminary experiment was conducted to determine the amount of water to add to the air-dried soil in each PVC cylinder to achieve field capacity. An initial weight of each soil-filled PVC cylinder was recorded after water had stopped draining from the cylinder bottom. The PVC cylinders were then re-positioned into their respective field plot locations and data were collected.

Every 48 hours at 0600 Hr for 22 days, the PVC cylinders were removed from their plot locations and weighed. The change in cylinder weight was assumed to be due to soil evaporative water loss. Next, percent volumetric water content (VWC) was measured by horizontal insertion of a Field Scout TDR 100 soil moisture probe (Spectrum Technologies, Plainfield, IL) into holes pre-drilled into the PVC cylinders at four depths (4-cm, 7-cm, 13-cm and 22-cm) below the cylinder soil surface. At each depth, the inserted probe measured VWC at the center of the soil cylinder column. After the VWC measurements, the PVC cylinders were immediately repositioned into their respective field plot locations.

Soil temperatures in one half of the PVC cylinders (n = 2) were recorded every 15-min at depths of 5-cm and 20-cm beneath the soil surface in half of the cylinders with Model 100 WatchDog data loggers (Spectrum Technologies, Plainfield, IL). Mulch surface temperatures were also recorded with an infrared thermometer (Oakton InfraPro, Vernon Hills, IL) on June 8, 2005 at 0600, 1000, 1400, 1800 and 2200 Hr under full sun conditions.

Data analysis. Several analyzes of variance were calculated for all data using a general linear model (JMP 5.0.1, SAS Institute Inc, 2002). Means and standard errors of the mean were calculated for soil temperatures at 5- and 30-cm depths, soil surface temperatures and mulch surface temperatures by measurement iteration. The research plots were arranged in a completely randomized experimental design. Analysis of variance (ANOVA) was calculated for statistical comparisons of integrated net radiation values by mulch treatment. If significant differences were found means were separated by Tukey's multiple comparisons test at the level $P \leq 0.05$ (JMP 5.0.1, SAS Institute Inc, 2002). A simple correlation analysis of summer net radiation and pyranometer measurements was calculated (JMP 5.0.1, SAS Institute Inc, 2002).

Evaporation experiment plots containing the four surface treatments with imbedded PVC cylinders were arranged in a randomized complete block design with four blocked replications. A one-way univariate model with surface mulch type as the independent variable was used for statistical comparisons of evaporative soil water loss.

Mulch thermal conductivity (k_m) was calculated according to:

$$k_m = G_m*(d /(T_{soil} – T_{surface}))$$

where G_m is the measured heat flux through the mulch (W/m^2), T_{soil} is the temperature of the soil surface below the mulch, $T_{surface}$ is the mulch surface temperature and d is mulch layer thickness (m).

Conductive heat transfer (C) through each mulch type was calculated according to Fourier's law of conductive heat transfer given by:

$$C = -k_m*((T_{soil} - T_{surface})/d)$$

where k_m is the thermal conductivity of the mulch (W/m°C), T_{soil} is the temperature of the soil surface below the mulch, $T_{surface}$ is the mulch surface temperature and d is mulch layer thickness (m).

Soil heat flux (G) was also calculated according to Fourier's law of conductive heat transfer given by:

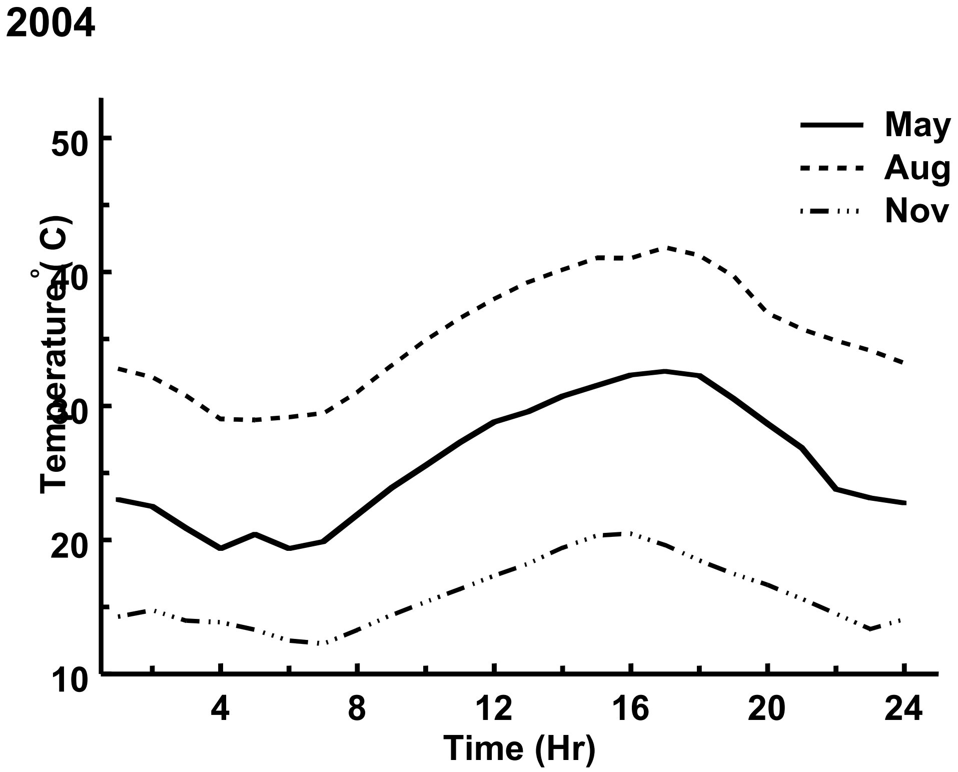
$$G = -k_s*((T_{soil30cm}-T_{soil5cm})/d)$$

where k_s is the thermal conductivity of the soil (assumed to be 0.5 W/m K at 7.7% soil moisture content, Abu-Hamdeh and Reeder, 2000), $T_{soil30cm}$ is the temperature of the soil at a 30-cm depth, $T_{soil5cm}$ is the temperature of the soil at a 5-cm depth and d (m) is the distance between them.

Results

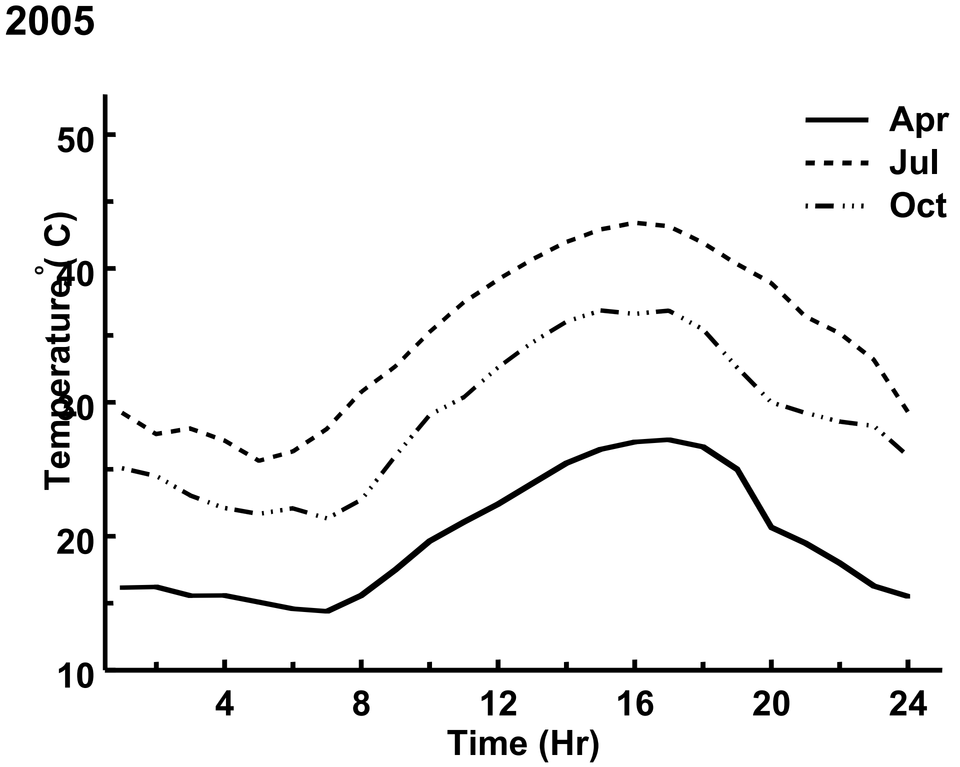
Figure 2.1 shows the diel patterns of mean monthly local ambient air temperatures during spring, summer and fall of 2004 and 2005 (data courtesy of the Central Arizona Project for Long Term Ecological Research Community Services Meteorological Station, Phoenix, AZ). The summer of 2004 was slightly climatologically warmer than 2005.

Mulch bulk density, thermal conductivity and albedo. Bulk density, thermal conductivity and albedo of the three landscape surface mulch treatments are shown in Table 2.1. Bulk density, thermal conductivity and albedo were higher for decomposing granite compared to landscape tree trimmings and ponderosa pine residue (Table 2.1). Initial albedo of shredded landscape tree trimmings and ponderosa pine residue was 0.17 and 0.14, respectively. After one growing season, albedo of landscape tree trimmings decreased to 0.16 and albedo of ponderosa pine residue increased to 0.16 (Table 2.1). Albedo of decomposing granite was 0.20 after one growing season and was assumed to be the same as the initial albedo (Table 2.1). Organic mulch albedo changed as the mulches aged; however, albedo over organic mulches remained lower than over decomposing granite (Table 2.1) or bare soil (0.18). Over the course of two growing seasons, shredded landscape tree trimmings decreased 48% in depth, ponderosa pine residue decreased 27% and decomposing granite decreased 19%.



2004

May
Aug
Nov
Temperature (°C)
50
40
30
20
10
4
8
12
16
20
24
Time (Hr)



2005

Apr
Jul
Oct
Temperature (°C)
50
40
30
20
10
4
8
12
16
20
24
Time (Hr)

Figure 2.1. Mean diel ambient air temperatures (°C) for May, August and November 2004 and April, July, and October 2005, Phoenix, Arizona.

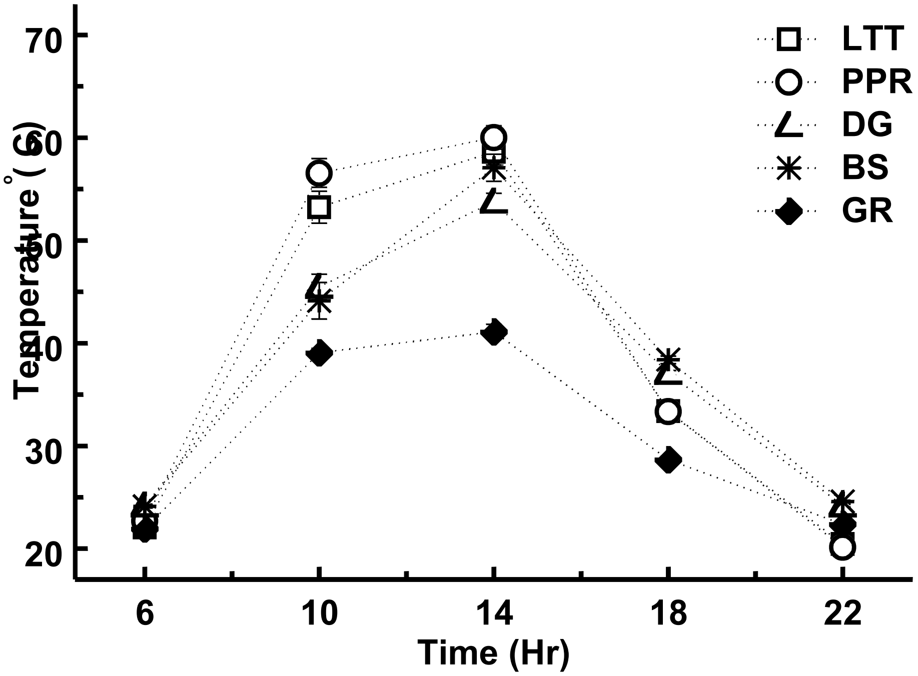
Table 2.1. Landscape surface mulch physical characteristics (± SE): particle size, bulk density, thermal conductivity, and albedo of landscape tree trimmings (LTT), ponderosa pine residue (PPR) and decomposing granite (DG).

Surface mulch	Mulch particle size grade	Bulk density (g/cm^3)	Thermal conductivity @ 38°C (W/m°C)	Albedo
LTT	Approx. 1.9-cm minus, unscreened	0.24 (0.08)	0.05 (0.002)	0.16 (0.003)
PPR	1.9-cm minus, screened	0.25 (0.08)	0.05 (0.002)	0.16 (0.003)
DG	0.6-cm minus, screened	1.69 (0.07)	0.18 (0.007)	0.20 (0.003)

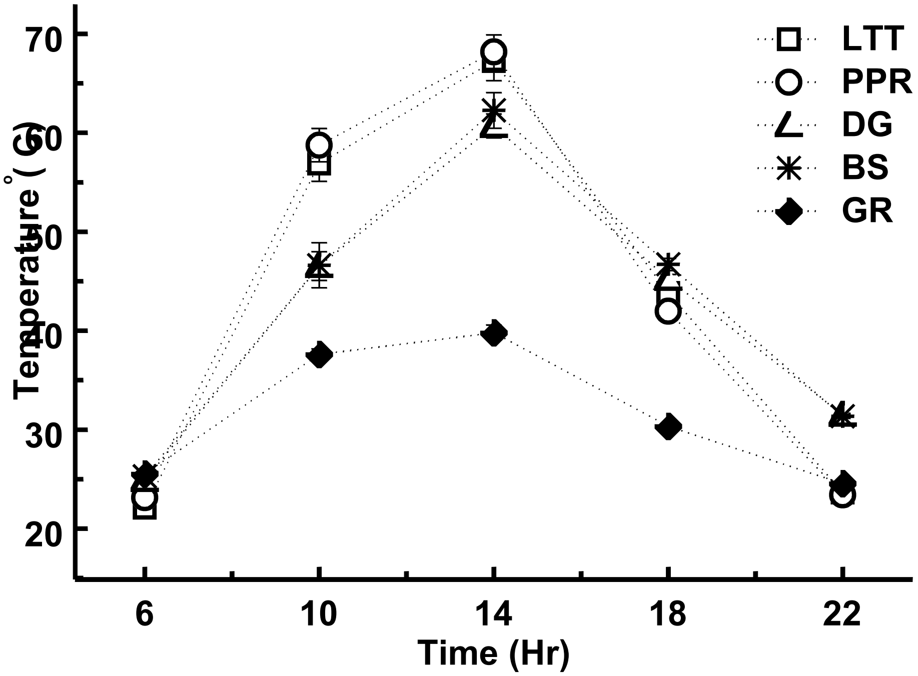
Temperature patterns at the landscape surface. Though landscape and soil surface temperatures were measured seasonally for two years, the presentation of mean diel patterns for only the summer months of August 2004 and July 2005 best demonstrates the ability of different surface mulch treatments to buffer the soil from intense radiation typical in a hot, desert climate. Summer daytime diel landscape surface temperatures were taken on typical, cloudless summer days in August 2004 and July 2005. The mean diel surface temperature fluctuation was greatest (45°C) over landscape tree trimming and ponderosa pine residue mulches during summer 2005 with a mean afternoon maximum temperatures of (1400 Hr) of 67°C and 68°C (Fig. 2.2B). The mean diel surface temperature fluctuation was also greatest over decomposing granite (36°C) and bare soil (37°C) during summer 2005 with mean maximum temperatures of 61°C and 62°C (Fig. 2.2B). The mean diel surface temperature fluctuation was greatest (19°C) over turf during summer 2004 with a mean maximum temperature of 41°C (Fig. 2.2A). Mean minimum diel surface temperatures tended to occur over the organic treatments (2200 Hr).

Soil surface temperature patterns beneath the mulch treatments. During summer months of both years, soil surface temperatures under decomposing granite mulch exceeded 40°C during the afternoon hours (Fig. 2.3A and B). The mean diel temperature fluctuation was greatest under decomposing granite: 15°C during summer 2004 and 19°C during summer 2005 with mean maximum of 44°C and 50°C (Fig. 2.3A and B). The mean diel temperature fluctuation under

A


70
60
50
40
30
20
Temperature (°C)
6
10
14
18
22
Time (Hr)
LTT
PPR
DG
BS
GR

B


70
60
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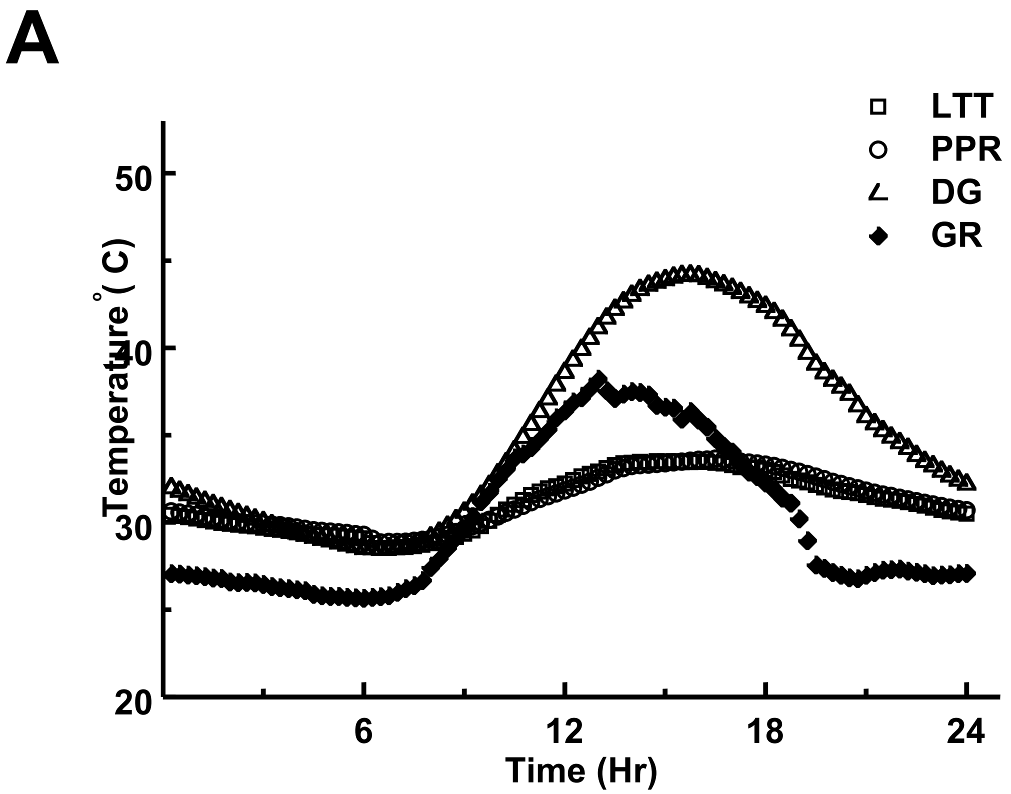
Temperature (°C)
6
10
14
18
22
Time (Hr)
LTT
PPR
DG
BS
GR

Figure 2.2. Effect of landscape surface mulch treatments on mean diel landscape surface temperatures during: A) August 2004 and B) July 2005. Landscape surface mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG), turf (GR) and bare soil (BS). Values are treatment means (LTT, PPR, DG n = 36 and GR, BS n = 18); vertical lines represent ± SE of the means; where not visible ± SE is smaller than symbol size.


A
LTT
PPR
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Temperature (°C)
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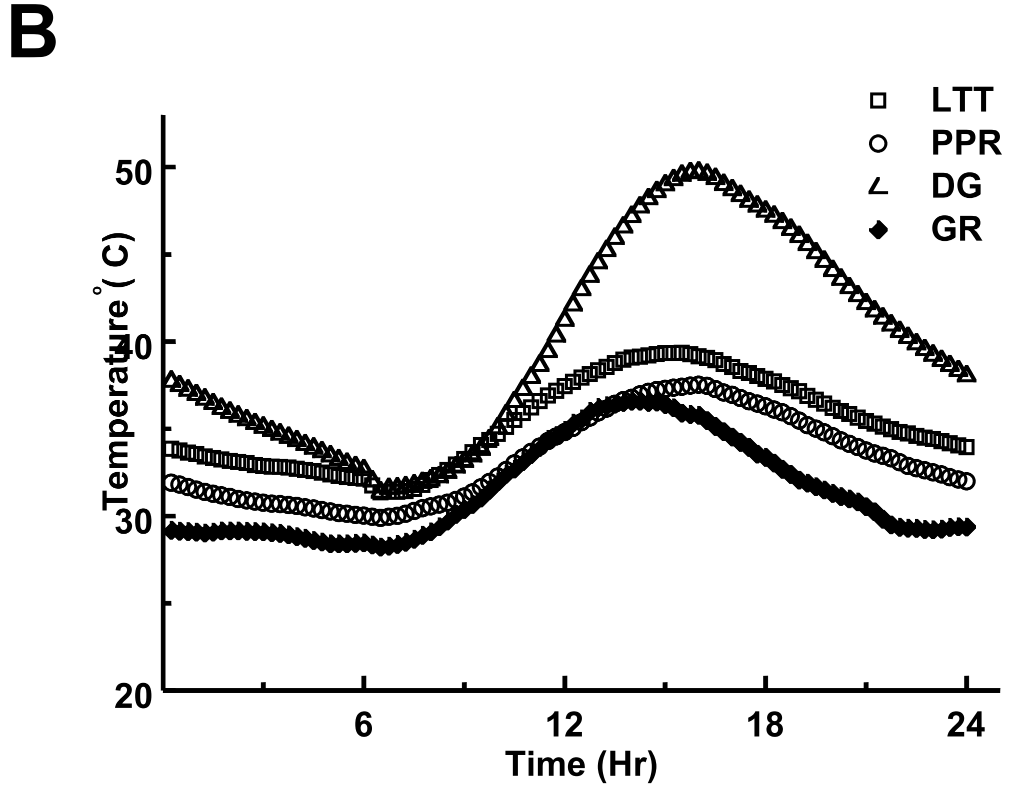
Time (Hr)


B
LTT
PPR
DG
GR
Temperature (°C)
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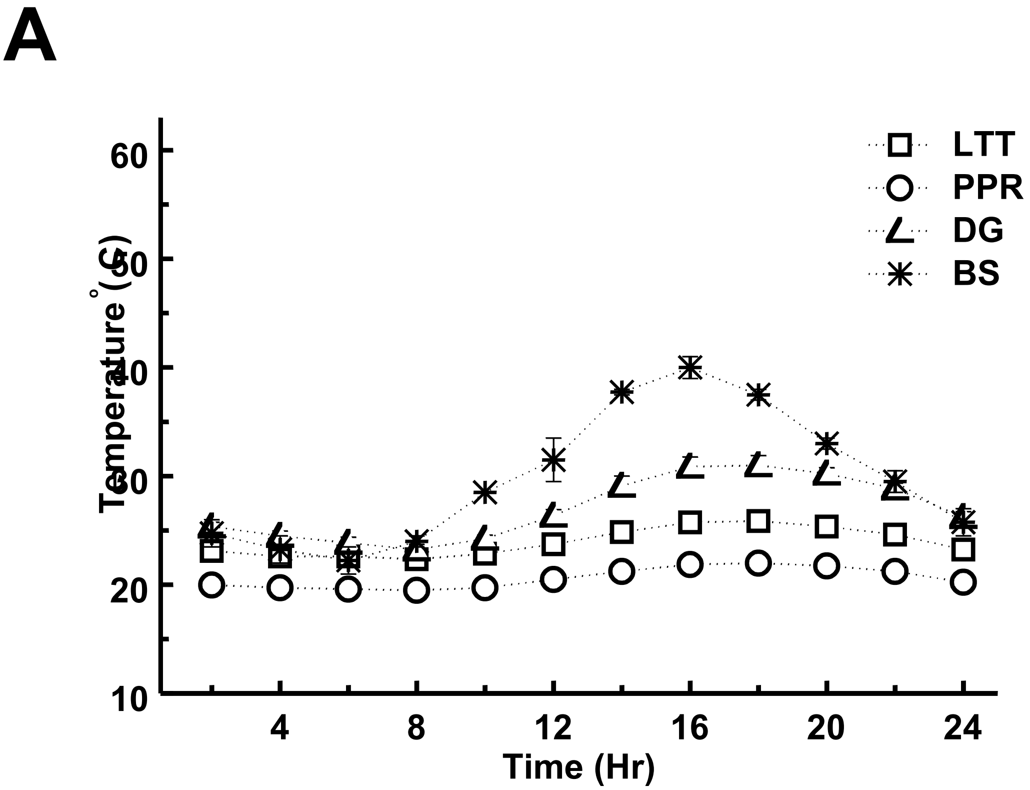
Time (Hr)

Figure 2.3. Effect of landscape surface mulch treatments on mean diel soil surface temperatures beneath the mulches and turf during: A) August 2004 and B) July 2005. Landscape surface mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG) and turf (GR). Values are treatment means (LTT, PPR, DG n = 4 and GR n = 2).

landscape tree trimmings, ponderosa pine residue and turf ranged from 5° to 12° degrees and never exceeded 40°C (Fig. 2.3A and B). During summer 2004 soil surface temperatures beneath landscape tree trimmings and ponderosa pine residue were very similar; however, during summer 2005 soil surface temperatures beneath ponderosa pine residue were slightly cooler than under landscape tree trimmings (Fig. 2.3A and B).

Landscape soil temperatures. Though soil temperatures at two depths (5- and 30-cm) were recorded continuously under landscape surface mulch treatments for two years, the presentation of only mean diel soil temperature data for the months of May, August, and November of 2004 and April, July, and October of 2005 is sufficient to show the capacity of different surface mulch treatments to modify the thermal environment of a landscape soil in a desert climate during the typical hot, desert seasons of spring, summer and fall (Fig. 2.4-2.7). Highest soil temperatures at both depths occurred during the seasonally hot summer months. Additionally, the amplitudes of diel variations in temperatures were greatest during the summer months and at the 5-cm depth. Mean diel temperature fluctuations tended to be lower during the spring and fall months and at the 30-cm depth, and were lowest in soils covered by the organic mulch treatments, landscape tree trimming and ponderosa pine residue mulch, and turf.

Soil temperatures at the 5-cm depth. In soils without surface mulch, mean temperatures exceeded 40^{o}C for at least some portion of the mean diel period


A
LTT
PPR
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Temperature °C
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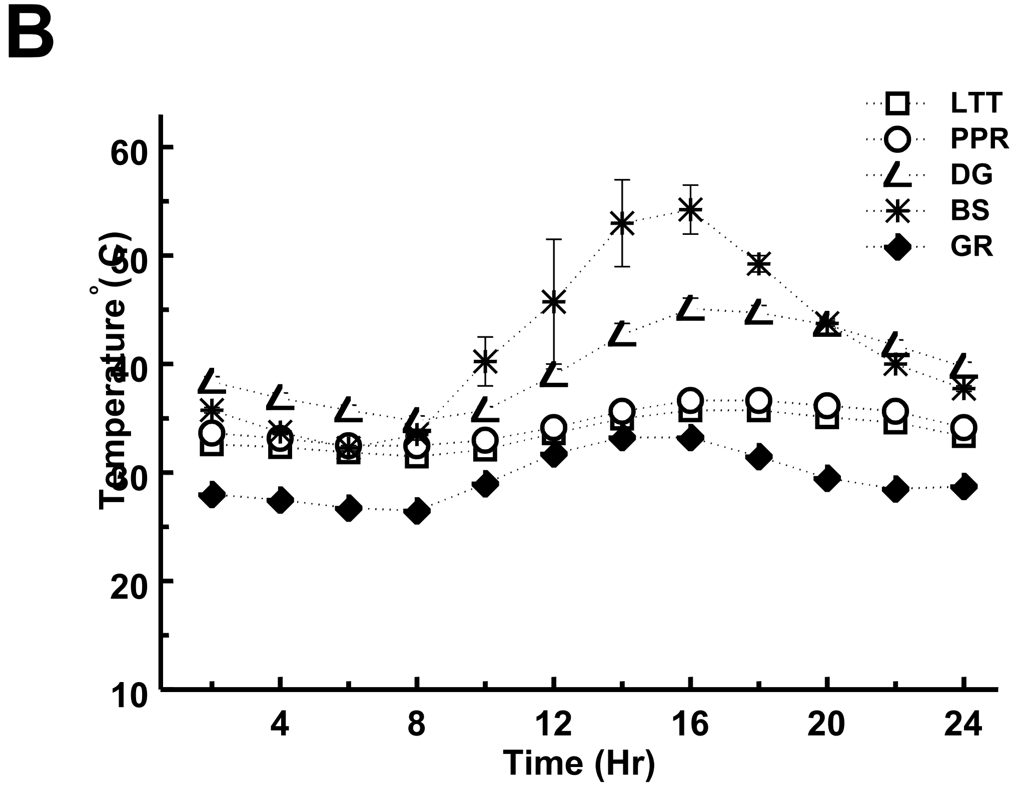
Time (Hr)


B
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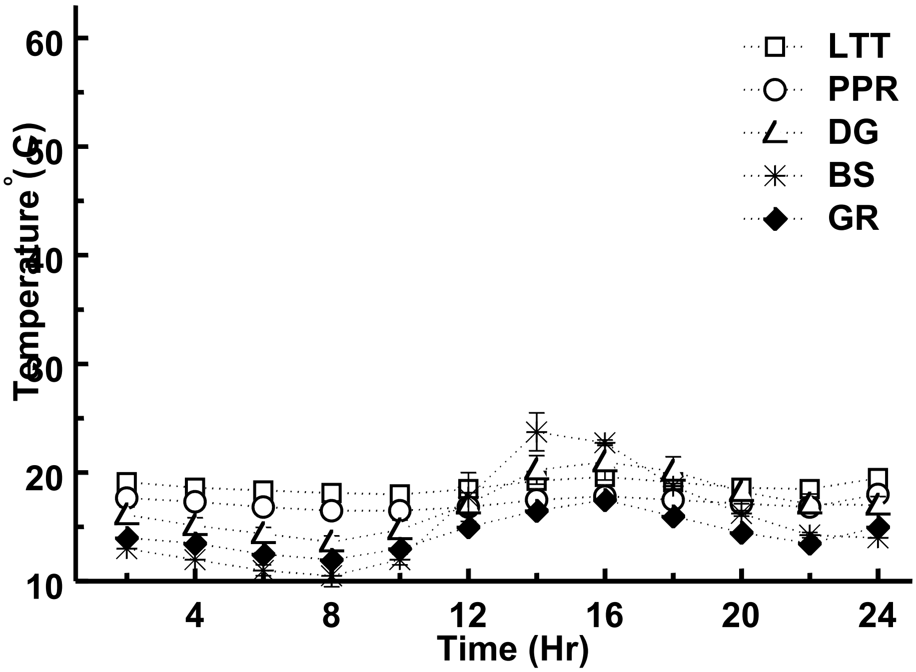
Time (Hr)

C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Temperature °(C)
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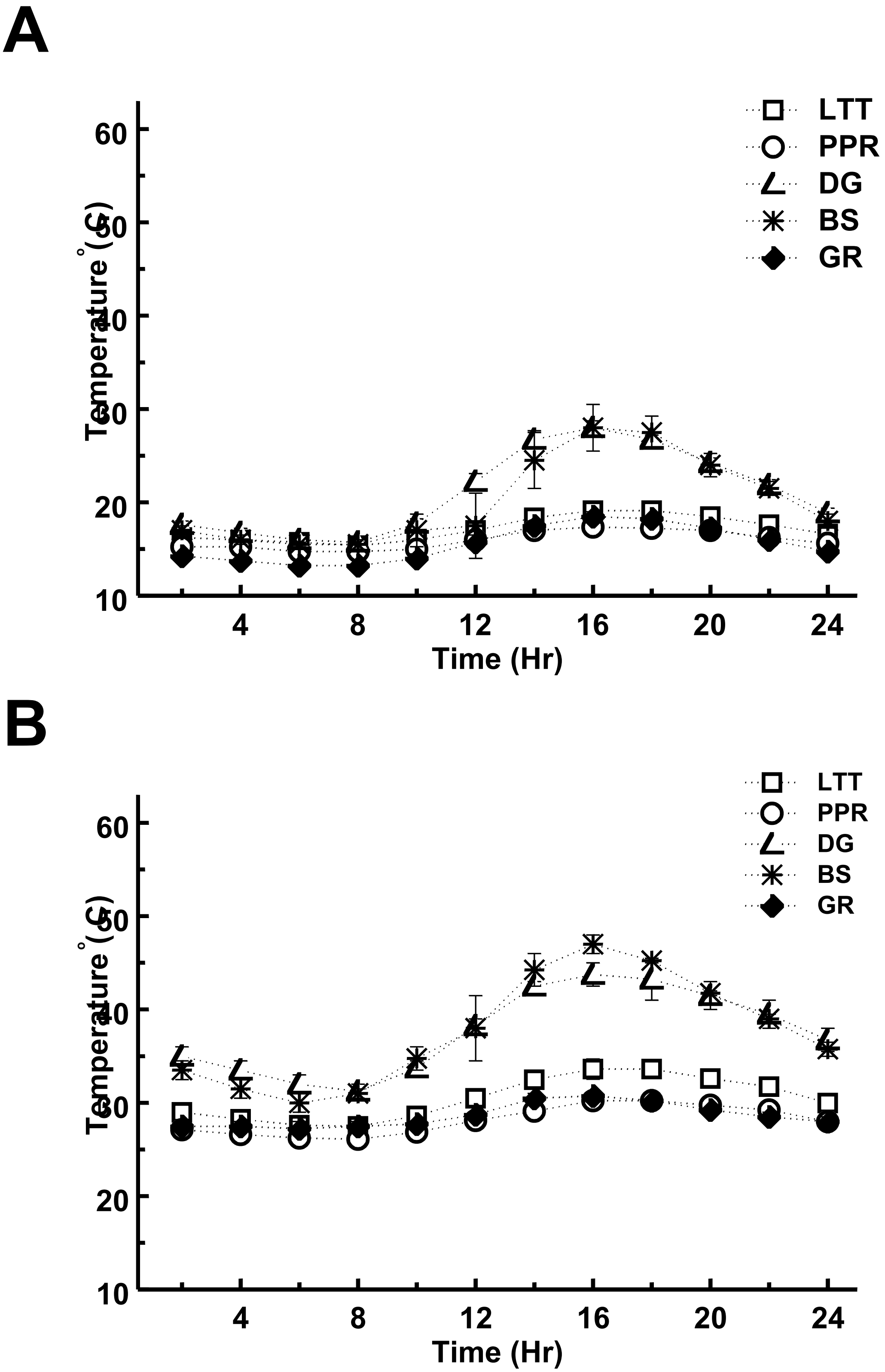
20
24
Time (Hr)
LTT
PPR
DG
BS
GR

Figure 2.4. Effect of landscape surface mulch treatments on mean diel soil temperatures at a 5-cm depth during: A) May 2004, B) August 2004 and C) November 2004. Landscape surface mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG), turf (GR) and bare soil (BS). Values are treatment means (LTT, PPR, DG n = 4 and GR, BS n = 2); vertical lines represent ± SE of the means; where not visible ± SE is smaller than symbol size.


A
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GR
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24
Time (Hr)
B
LTT
PPR
DG
BS
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Temperature (°C)
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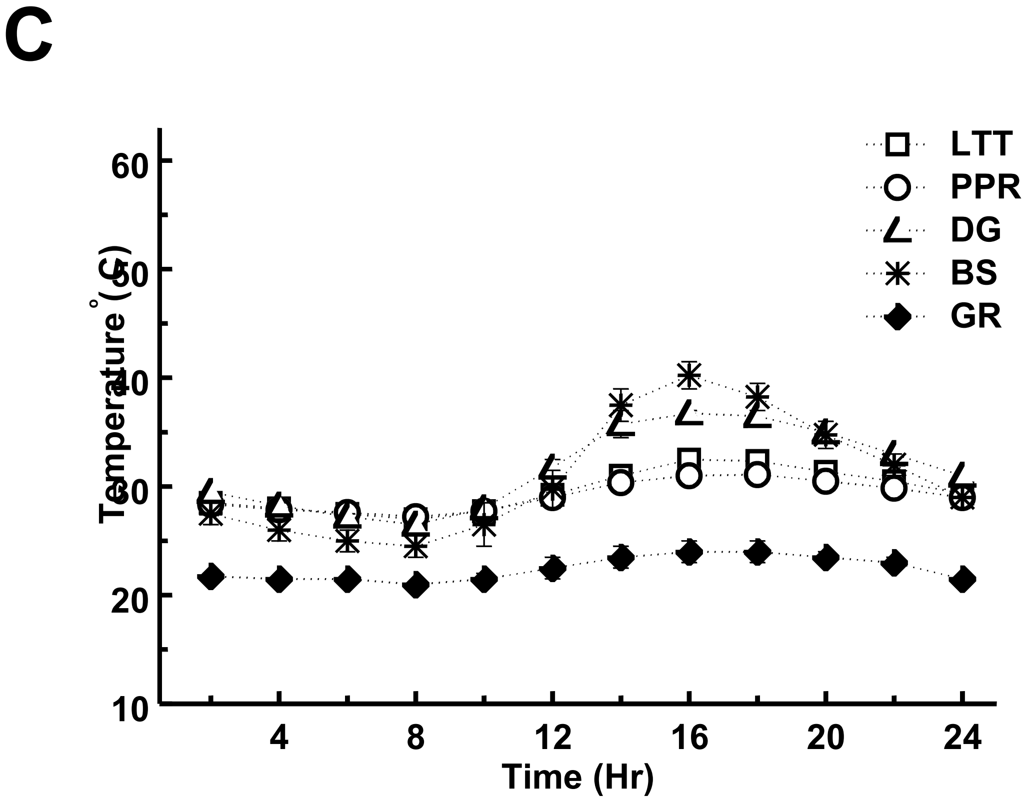
Time (Hr)


C
Temperature °(C)
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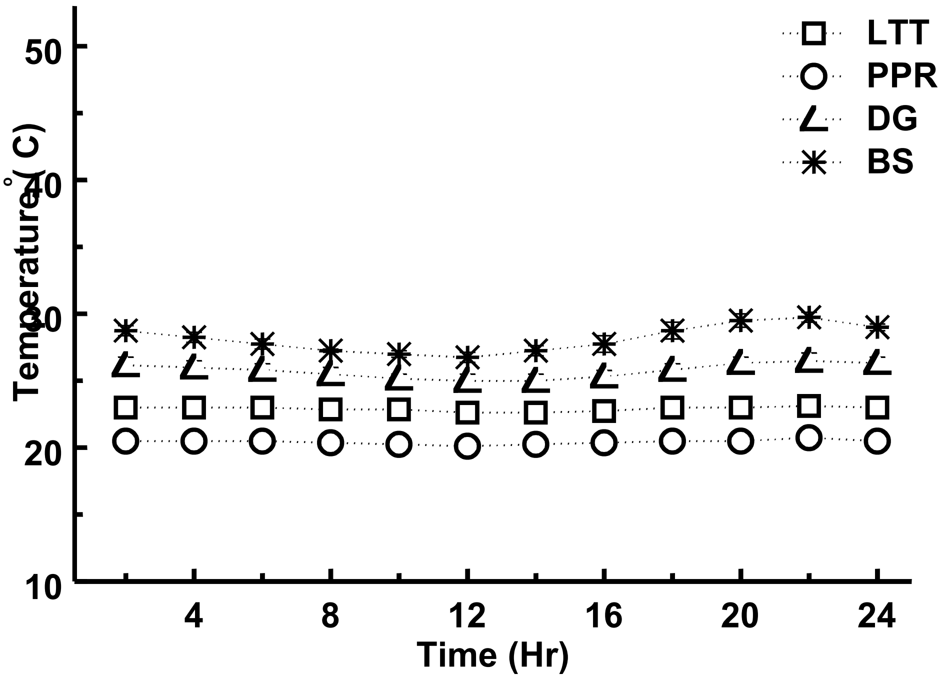
24
Time (Hr)
LTT
PPR
DG
BS
GR

Figure 2.5. Effect of landscape surface mulch treatments on mean diel soil temperatures at a 5-cm depth during: A) April 2005, B) July 2005 and C) October 2005. Landscape surface mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG), turf (GR) and bare soil (BS). Values are treatment means (LTT, PPR, DG n = 4 and GR, BS n = 2); vertical lines represent ± SE of the means; where not visible ± SE is smaller than symbol size.

A


LTT
PPR
DG
BS
Temperature (°C)
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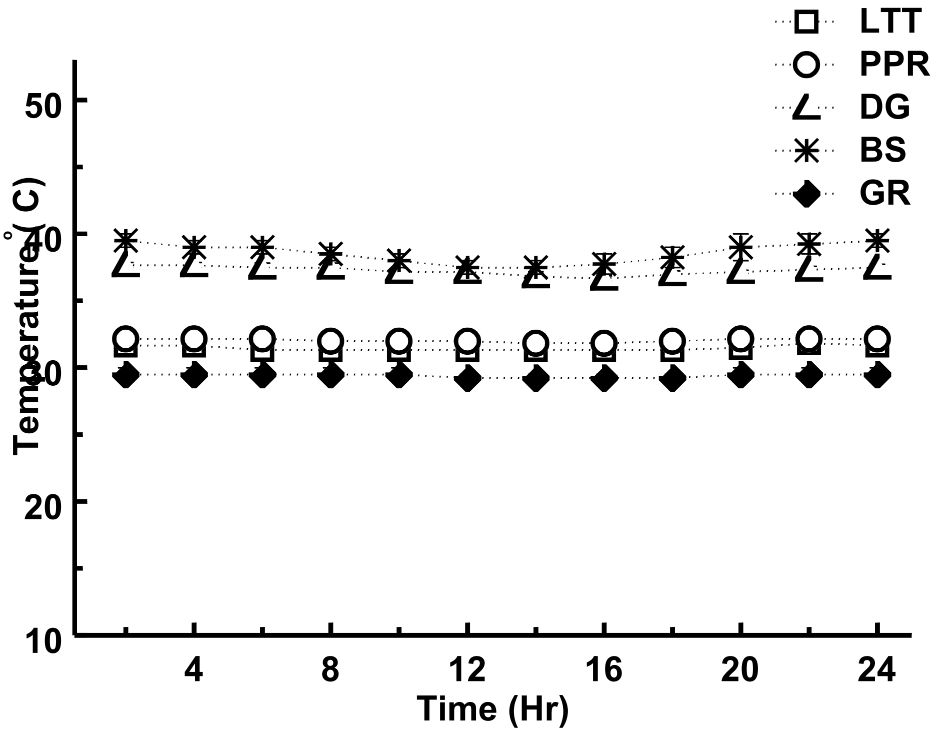
24
Time (Hr)

B


LTT
PPR
DG
BS
GR
Temperature (°C)
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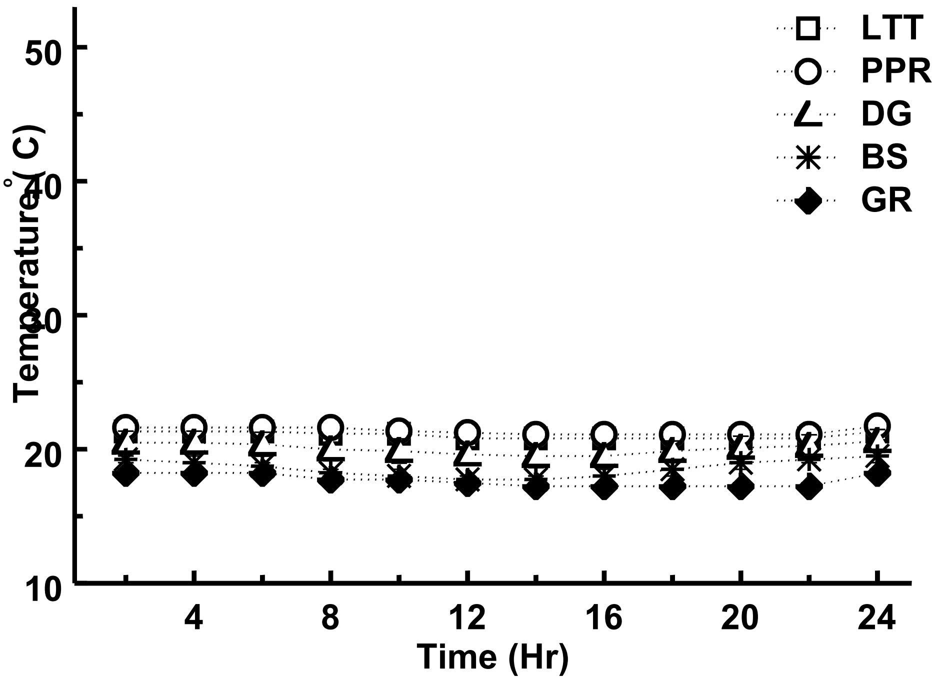
24
Time (Hr)

C


LTT
PPR
DG
BS
GR
Temperature ° (C)
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40
30
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10
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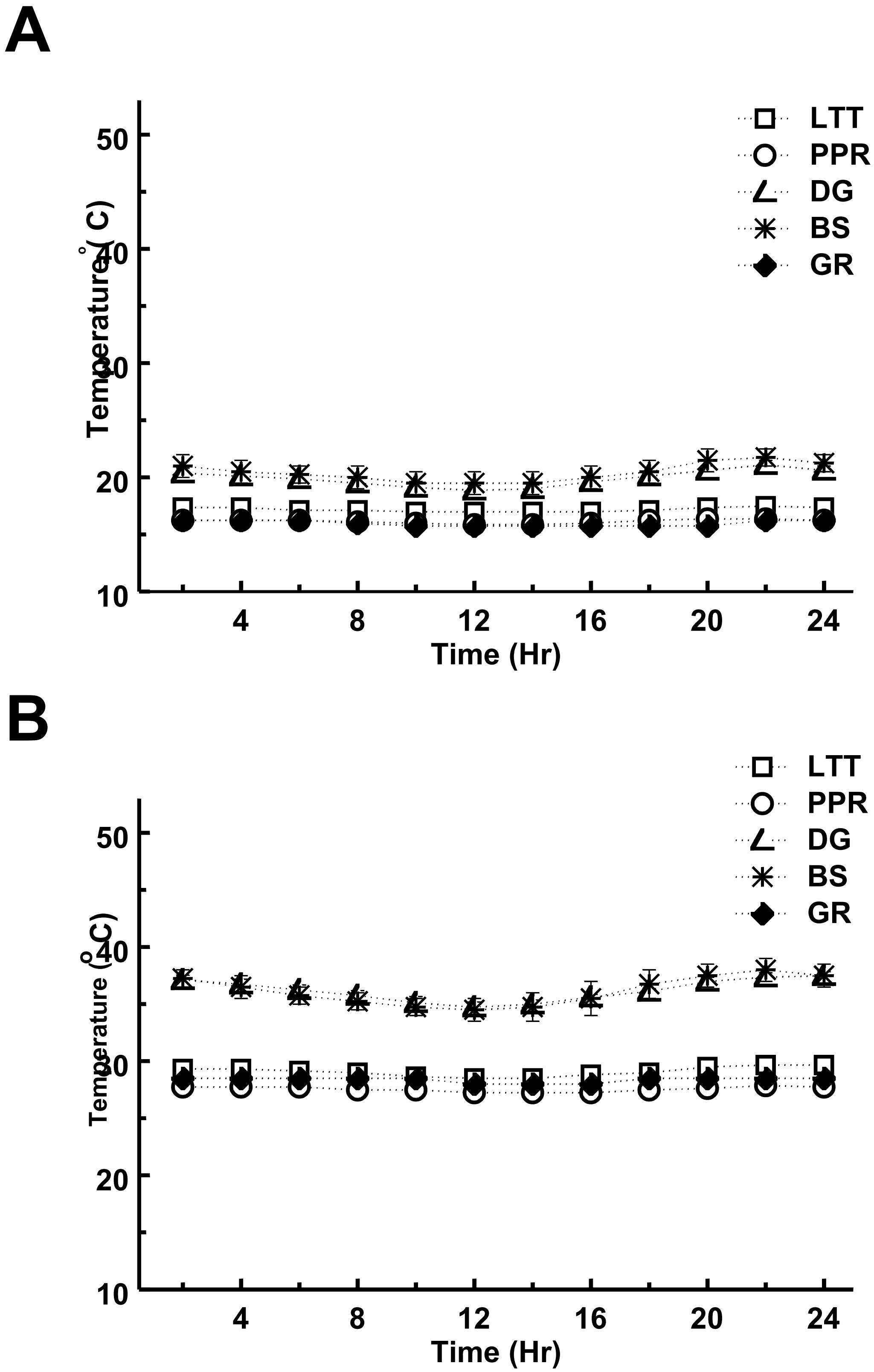
16
20
24
Time (Hr)

Figure 2.6. Effect of landscape surface mulch treatments on mean diel soil temperatures at a 30-cm depth during: A) May 2004, B) August 2004 and C) November 2004. Landscape surface mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG), turf (GR) and bare soil (BS). Values are treatment means (LTT, PPR, DG n = 4 and GR, BS n = 2); vertical lines represent ± SE of the means; where not visible ± SE is smaller than symbol size.


A
LTT
PPR
DG
BS
GR
Temperature (°C)
50
40
30
20
10
4
8
12
16
20
24
Time (Hr)
B
LTT
PPR
DG
BS
GR
Temperature (°C)
50
40
30
20
10
4
8
12
16
20
24
Time (Hr)

C

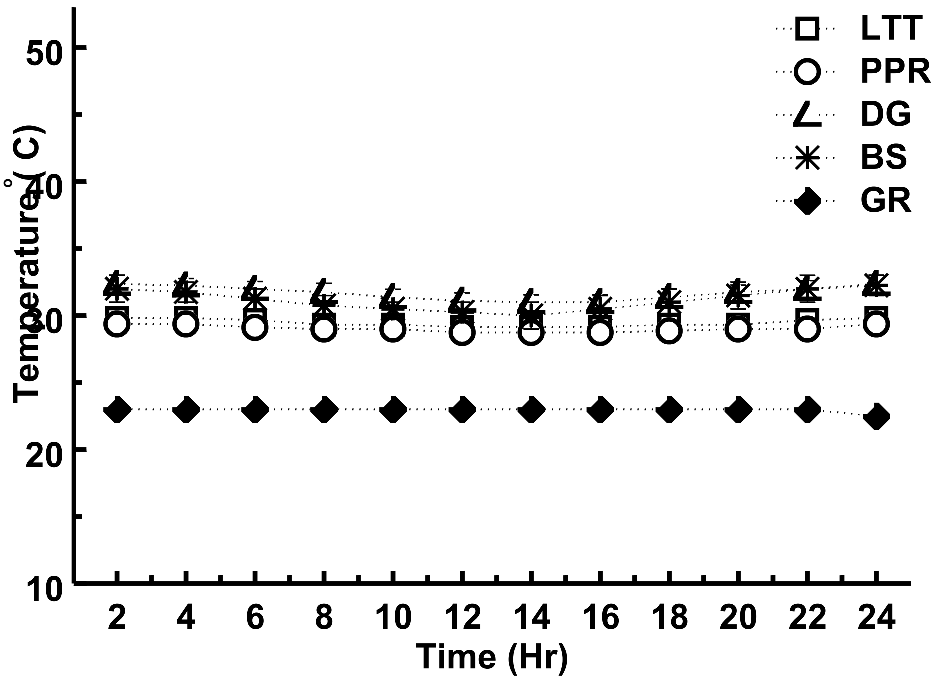

LTT
PPR
DG
BS
GR
50
40
30
20
10
Temperature °(C)
2
4
6
8
10
12
14
16
18
20
22
24
Time (Hr)

Figure 2.7. Effect of landscape surface mulch treatments on mean diel soil temperatures at a 30-cm depth during: A) April 2005, B) July 2005 and C) October 2005. Landscape surface mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG), turf (GR) and bare soil (BS). Values are treatment means (LTT, PPR, DG n = 4 and GR, BS n = 2); vertical lines represent ± SE of the means; where not visible ± SE is smaller than symbol size.

except during April 2005 (Fig. 2.4 and 2.5). In soil covered by decomposing granite, mean temperatures also exceeded 40^{o}C for a portion of mean diel period, but only during the summer months of both years (Fig. 2.4B and 2.5B). The mean diel temperature fluctuation in soil without surface mulch was greatest (22^{o}C) during summer 2004 with a mean afternoon (1600 Hr) maximum of 54°C (Fig. 2.4B). The mean diel temperature fluctuation in soil covered with decomposing granite mulch was also greatest (10^{o}C) during summer 2004 with a mean maximum temperature of 45^{o}C. Mean diel temperature fluctuation in soils covered with landscape tree trimmings, ponderosa pine residue, or turf ranged from only 2^{o} to 6^{o}C and maximum temperatures never exceeded 40^{o}C (Fig. 2.4-2.5). Mean minimum diel soil temperatures tended to occur during morning hours (600 to 800 Hr).

Soil temperatures at the 30 cm depth. Regardless of month, mean diel fluctuations in soil temperatures at the lower depth were $\leq$ 3^{o}C (Fig. 2.6-2.7) and did not exceed 40^{o}C. During the summer months of both years, the mean temperature of soils without a landscape surface mulch or covered with decomposing granite was about 37^{o}C and was about 8^{o}C higher than the temperature of soils covered with either landscape tree trimmings, ponderosa pine residue or turf. Surface mulch treatments appeared to have the least effect on mean diel soil temperature patterns during the fall months (Fig 2.6C and 2.7C).

Net radiation patterns above landscape surface mulches. Though net radiation was measured seasonally for two years, the presentation of mean diel patterns for only the summer months of August 2004 and July 2005 best demonstrates the ability of different surface mulch treatments to buffer the soil from intense radiation typical in a hot, desert climate. Mean values of net radiation over the surface mulch treatments were positive during the day and negative during the night. Positive summer patterns of diel net radiation were positively correlated to mean insolation ($r = 0.9188$). Daytime net radiation values were generally highest over turf ($P < 0.0001$ and $P = 0.0008$, Table 2.2). Daytime net radiation values over decomposing granite, landscape tree trimming, and ponderosa pine residue mulches were similar (Table 2.2). Nighttime net radiation values were most negative over bare soil and decomposing granite (Fig. 2.8A and B). Nighttime net radiation values above landscape tree trimmings, ponderosa pine residue and turf were generally less negative ($P < 0.0001$, Table 2.2).

Landscape surface mulches and patterns of heat transfer. Thermal data recorded in August 2004 and July 2005 and experimentally derived mulch thermal conductivity values were used to calculate estimates of conductive heat transfer (C) through the mulch (Fig. 2.9). The highest diel range of C occurred in soil mulched with decomposing granite (84 W/m^2 and 82 W/m^2 in August 2004 and July 2005, respectively). In comparison, additions of organic surface mulch reduced the diel range of C. The diel range of C under landscape tree trimmings

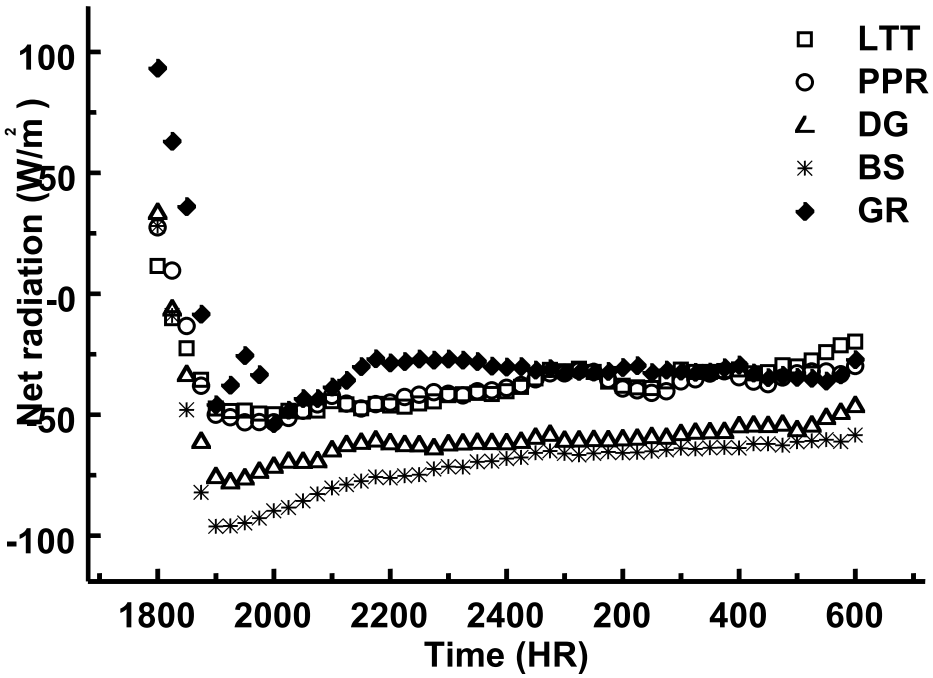
Table 2.2. Mean integrated net radiation values (MJ/m^2) over landscape tree trimmings (LTT), ponderosa pine residue (PPR), turf grass (GR), decomposing granite (DG) and bare soil (BS) by day (0600 to 1800 HR) and night (1800 to 0600 HR) during summer (2004 and 2005).

	Net Radiation (MJ/m^2)			
	2004		2005	
Treatment	Day	Night	Day	Night
LTT	10.77^{z}b^y	-1.61 a	12.97 b	-1.59 a
PPR	9.35 b	-1.60 a	12.78 b	-1.66 a
GR	16.60 a	-1.24 a	16.84 a	-0.72 a
DG	10.43 b	-2.57 b	11.23 b	-2.73 b
BS	10.35 b	-2.75 b	12.97 b	-2.67 b

[z] Values are treatment means, n = 4.

[y] Mean values within the same column followed by the same letter were not significantly different, using Tukey's HSD test ($\alpha = 0.05$).

A


Net radiation (W/m^2)
100
50
-0
-50
-100
1800
2000
2200
2400
200
400
600
Time (HR)
□ LTT
○ PPR
∠ DG
✳ BS
◆ GR

B

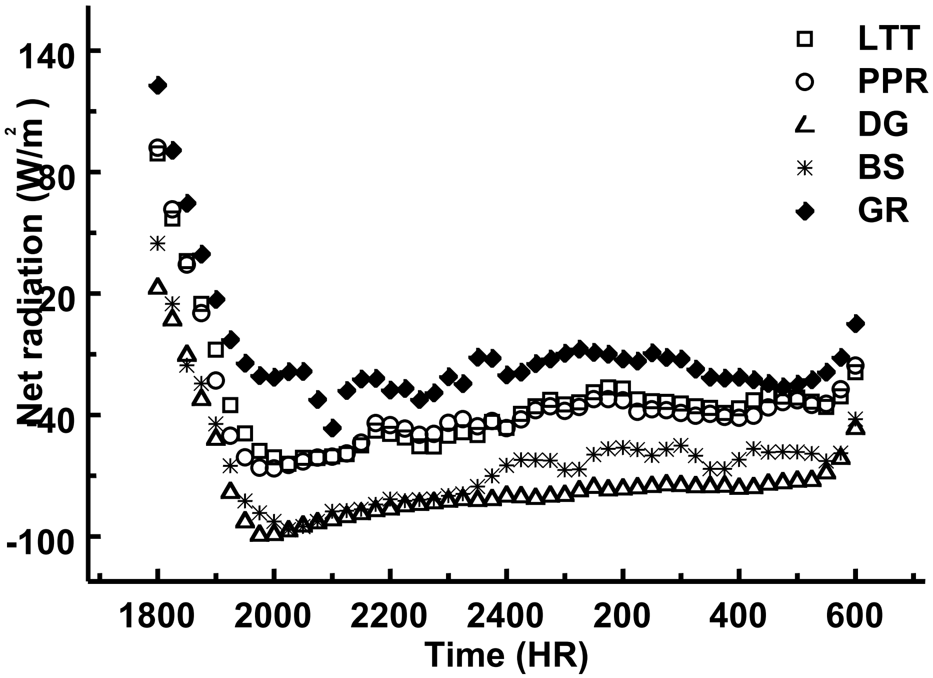
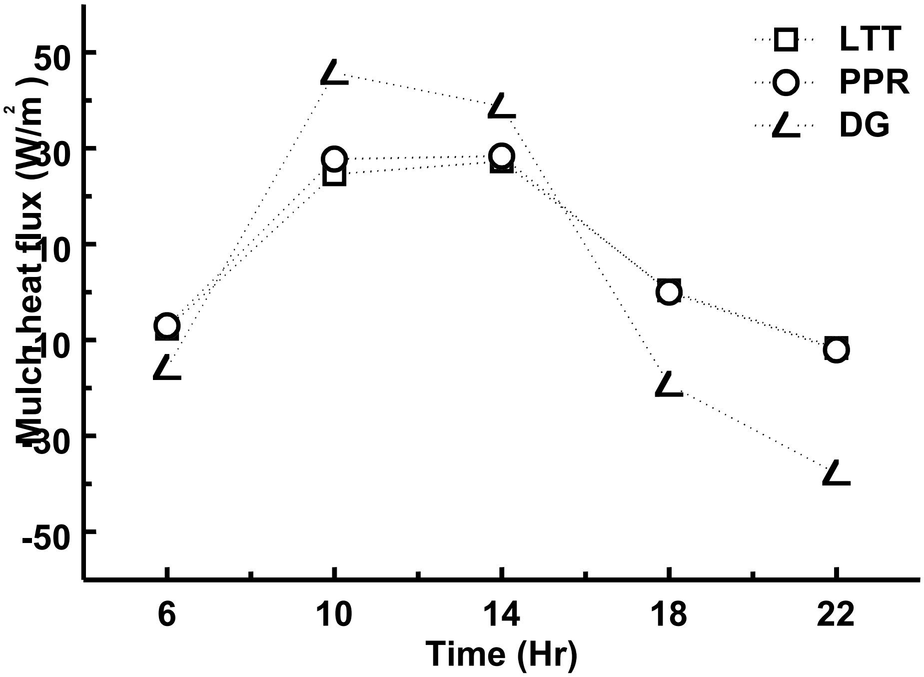

Net radiation (W/m^2)
140
80
20
-40
-100
1800
2000
2200
2400
200
400
600
Time (HR)
□ LTT
○ PPR
∠ DG
✳ BS
◆ GR

Figure 2.8. Mean nighttime net radiation (W/m^2) during A) August 2004 and B) July 2005. Landscape surface mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), turf (GR), decomposing granite (DG) and bare soil (BS). Values are treatment means (LTT, PPR, DG n = 4 and GR, BS n = 2).

A


LTT
PPR
DG
Mulch heat flux (W/m^2)
50
30
10
-10
-30
-50
6
10
14
18
22
Time (Hr)

B

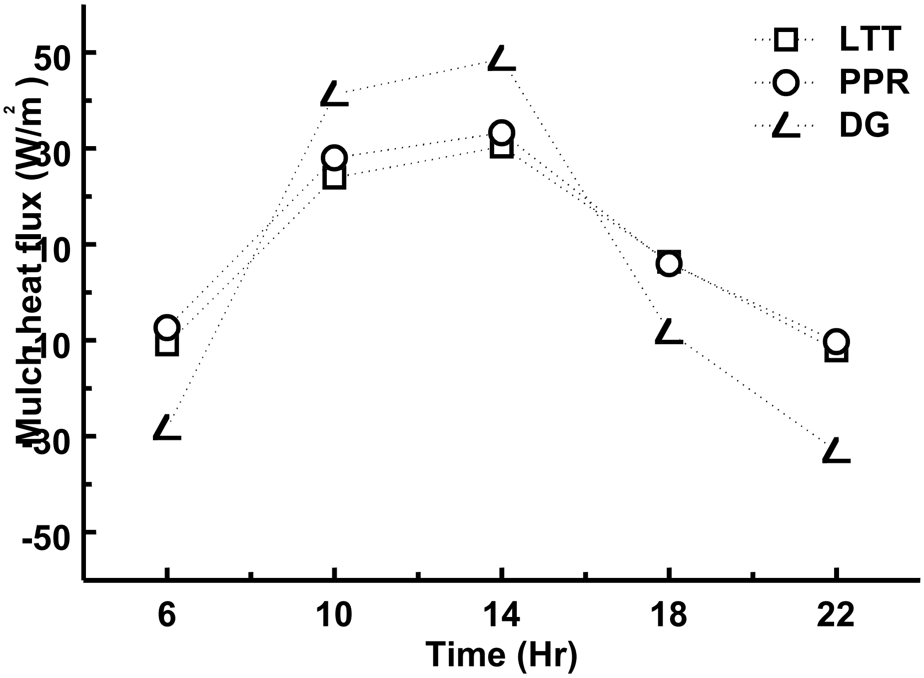

LTT
PPR
DG
Mulch heat flux (W/m^2)
50
30
10
-10
-30
-50
6
10
14
18
22
Time (Hr)

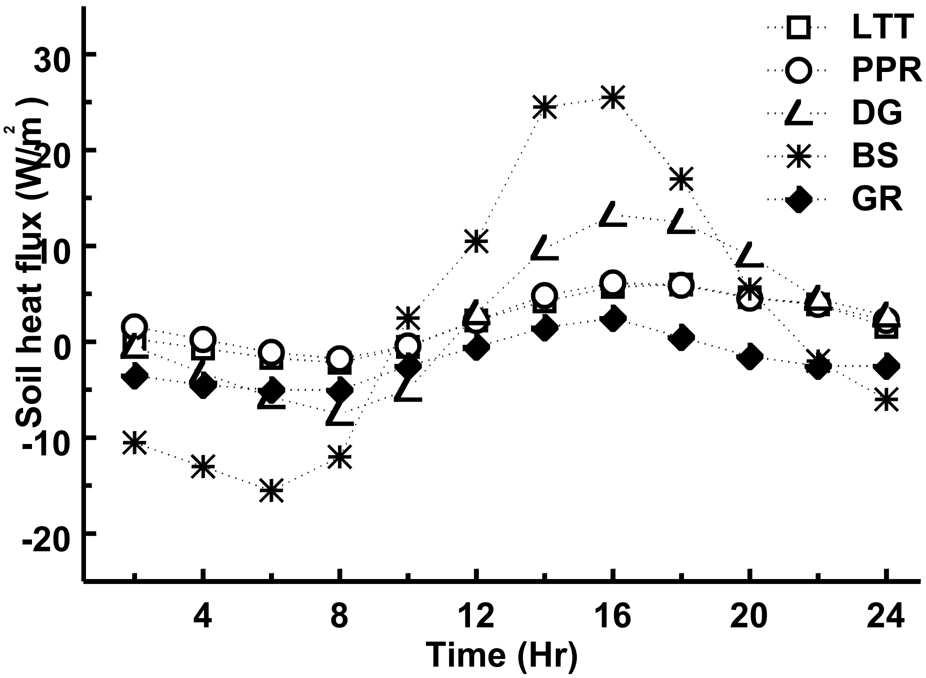
Figure 2.9. Mean calculated mulch conductive heat transfer (W/m^2) during A) August 2004 and B) July 2005. Landscape surface mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR) and decomposing granite (DG). Values are treatment means (n = 4).

was 39 W/m^2 and 43 W/m^2 for August 2004 and July 2005. The diel range of C under ponderosa pine residue was 40 W/m^2 and 44 W/m^2 for August 2004 and July 2005.

Landscape surface mulches and patterns of soil heat flux. Soil heat flux (G) estimates were calculated from thermal data recorded in August 2004 and July 2005 (Fig. 2.10) showed that the highest diel range of G occurred in soil without surface mulch (42 W/m^2 and 39 W/m^2 in August 2004 and July 2005, respectively). In comparison, additions of surface mulch differentially reduced the diel range of G. Specifically, the diel range of G under decomposing granite was 21 W/m^2 and 26 W/m^2 for August 2004 and July 2005. The diel range G under landscape tree trimmings was 8 W/m^2 and 17 W/m^2 for August 2004 and July 2005. The diel range of G under ponderosa pine residue was 8 W/m^2 and 10 W/m^2 for August 2004 and July 2005. The diel range of G under turf was 8 W/m^2 and 11 W/m^2 for August 2004 and July 2005.

Landscape surface mulches and soil water evaporation. Soil in cylinders that were not treated with surface mulch evaporated significantly more soil water than soils treated with surface mulch ($P < 0.0001$, Fig. 2.11). Soil in cylinders treated with landscape tree trimmings lost the least amount of soil water compared to all other treatments (Fig. 2.11). Soil in cylinders mulched with ponderosa pine residue evaporated soil water at a similar rate to landscape tree trimmings at the beginning of the experiment, but increased water loss such that

A


LTT
PPR
DG
BS
GR
Soil heat flux (W/m²)
30
20
10
0
-10
-20
4
8
12
16
20
24
Time (Hr)

B

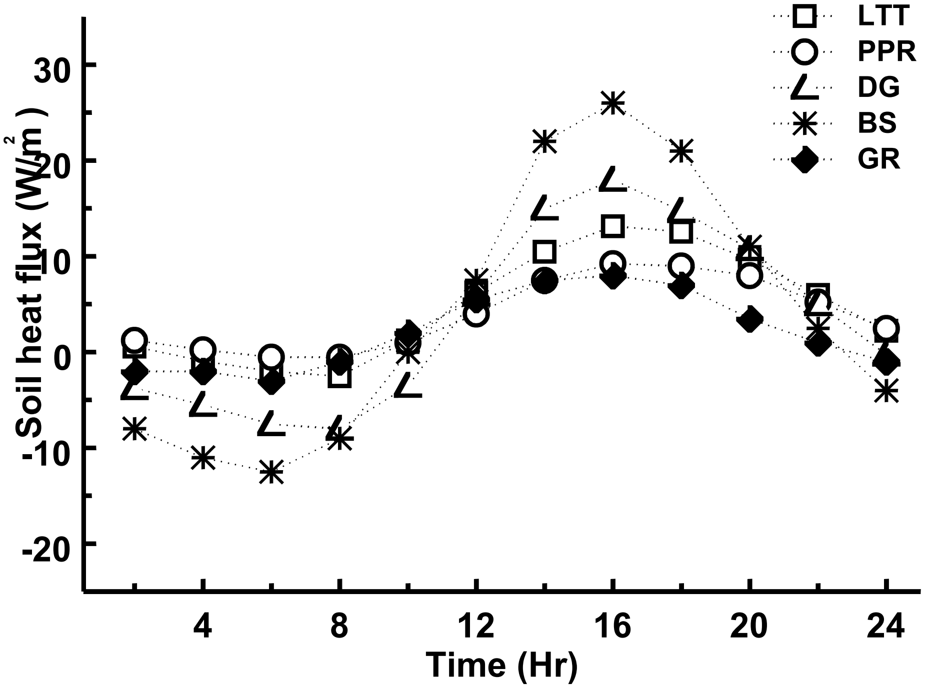

LTT
PPR
DG
BS
GR
Soil heat flux (W/m²)
30
20
10
0
-10
-20
4
8
12
16
20
24
Time (Hr)

Figure 2.10. Mean calculated soil heat flux (W/m^2) during A) August 2004 and B) July 2005. Landscape surface mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG), turf (GR) and bare soil (BS). Values are treatment means (LTT, PPR, DG n = 4 and GR, BS n = 2).

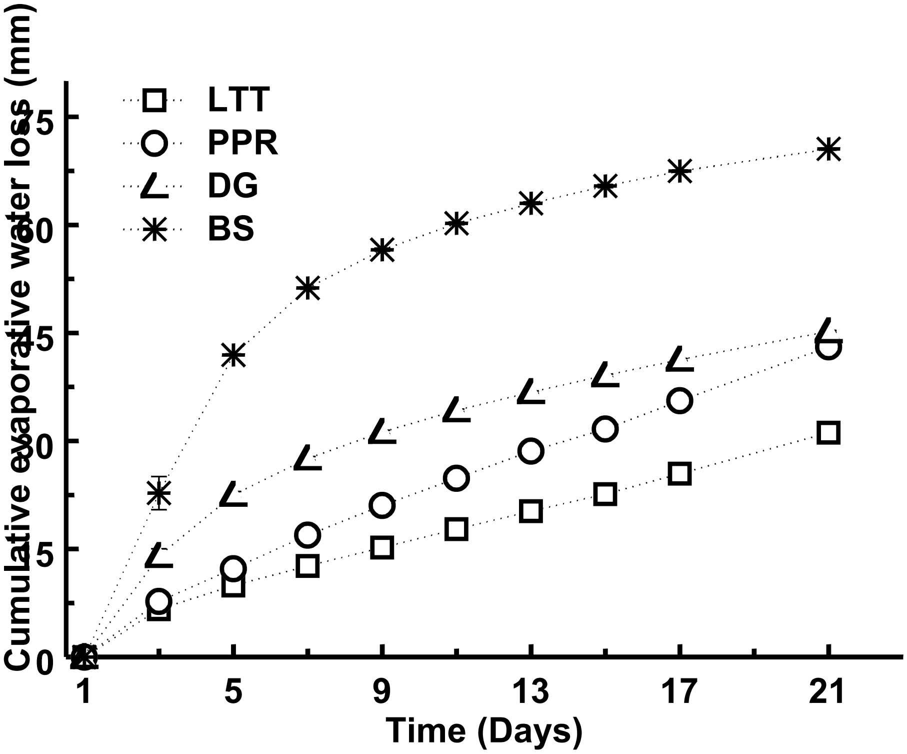
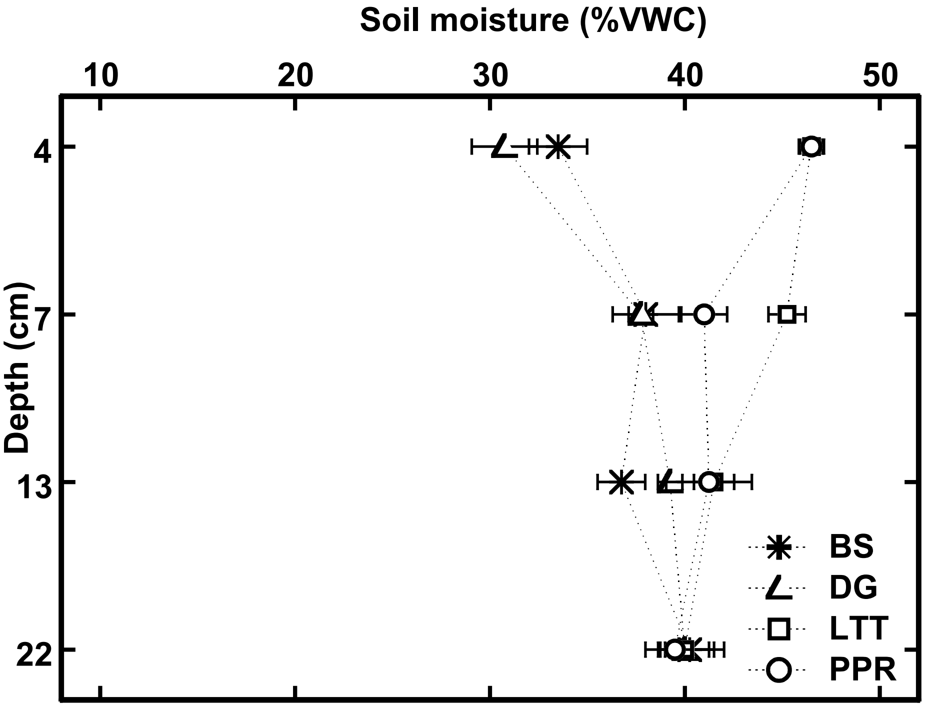

LTT
PPR
DG
BS
Cumulative evaporative water loss (mm)
75
60
45
30
15
0
1
5
9
13
17
21
Time (Days)

Figure 2.11. Cumulative evaporative water loss (mm) during June 2005 from soil in open-field evaporation cylinders under landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG) and bare soil (BS). Values are treatment means (n = 4); vertical lines represent ± SE of the means; where not visible ± SE is smaller than symbol size.

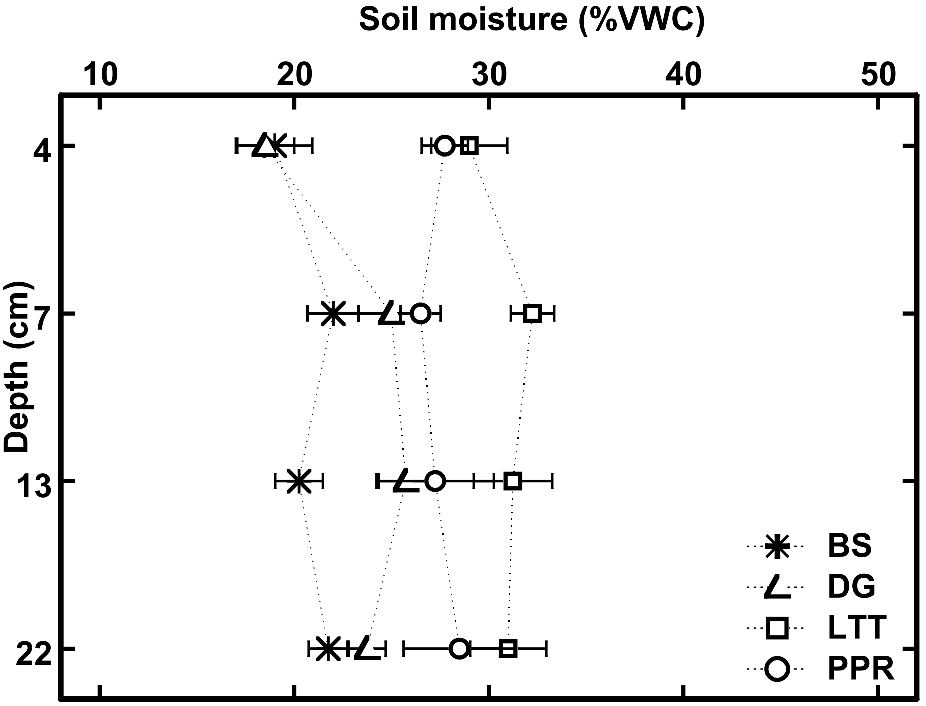
cumulative water loss under ponderosa pine residue was more similar to decomposing granite than landscape tree trimmings by the end of the experiment (Fig. 2.11).

Percent VWC was generally higher under organic mulches (Fig. 2.12). After three days in the field plots, soil VWC was higher at the 4-cm depth under landscape tree trimmings and ponderosa pine residue than decomposing granite and bare soil; however, lower depths had similar VWC (Fig. 2.12). By day seven soil moisture was higher under landscape tree trimmings and ponderosa pine residue, especially at the 4-cm depth (Fig. 2.12). By day 13 and continuing on to day 21, soil VWC in the cylinders was fairly constant by treatment at all four depths (Fig. 2.12).

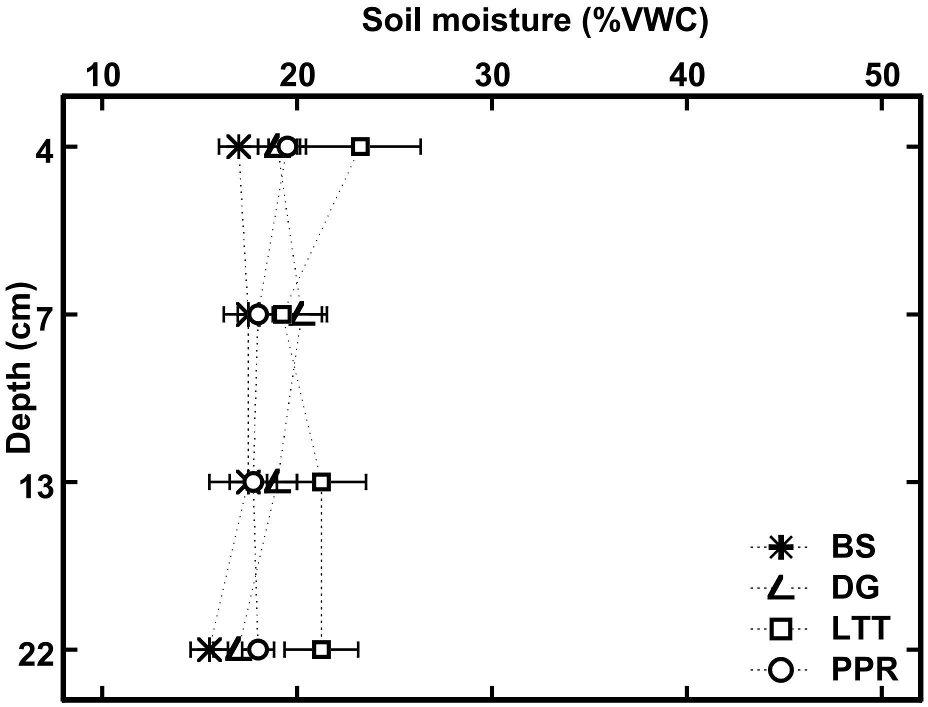
A


Soil moisture (%VWC)
10
20
30
40
50
Depth (cm)
4
7
13
22
BS
DG
LTT
PPR

B


Soil moisture (%VWC)
10
20
30
40
50
Depth (cm)
4
7
13
22
BS
DG
LTT
PPR

C


Soil moisture (%VWC)
10
20
30
40
50
Depth (cm)
4
7
13
22
BS
DG
LTT
PPR

D

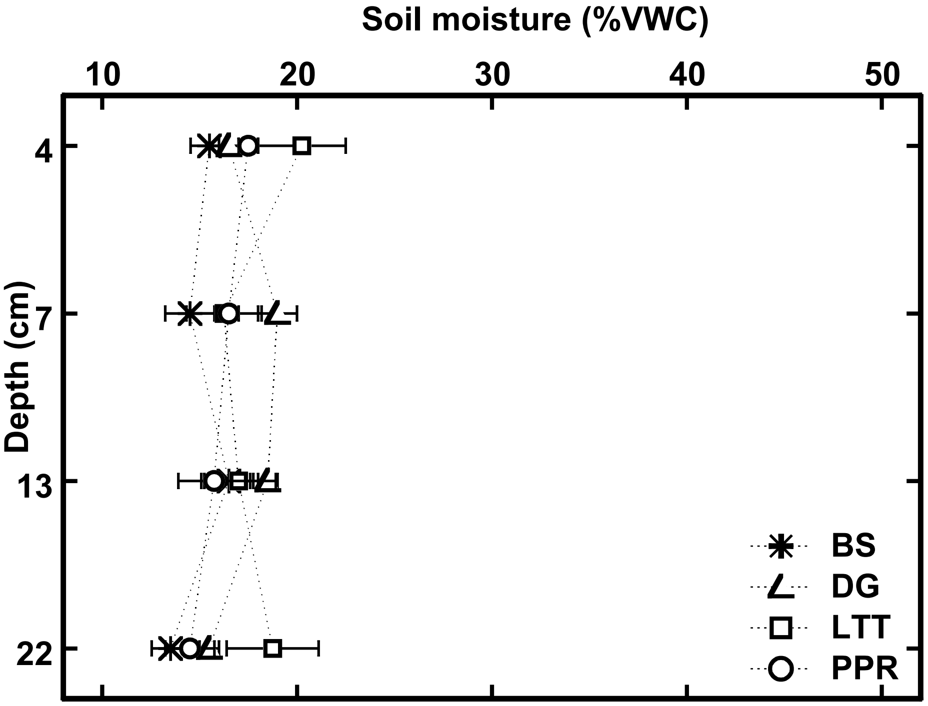

Soil moisture (%VWC)
10
20
30
40
50
Depth (cm)
4
7
13
22
BS
DG
LTT
PPR

Figure 2.12. Effects of landscape surface mulches on soil moisture (% VWC) in open-field evaporation cylinders 4-, 7-, 13- and 22-cm below the soil surface on A) Day 3, B) Day 7, C) Day 13 and D) Day 21. Landscape surface mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG) and bare soil (BS). Values are treatment means (n = 4); horizontal lines represent ± SE of the means.

Discussion

Previous research (Ashworth and Harrison, 1983; Iles and Dosmann, 1999; Montague et al, 1998 and 2000; Pickering et al, 1998) on the effects of landscape surface mulches has been carried out in climates that are more temperate and mesic than the hot, desert climate of Phoenix, AZ. The focus of this research was to determine the effectiveness of organic and inorganic mulches at managing the harsh thermal environment in a landscape characterized by intense radiation and extreme aridity throughout the growing season. Organic mulches better protected the soil from intense solar radiation than the inorganic mulch or bare soil. The ability of surface mulches to moderate landscape soil environments is a function of mulch thermal properties such as bulk density, thermal conductivity, albedo and mulch layer thickness. Consequently, organic mulches in a hot, desert climate have higher surface temperatures, less negative nighttime net radiation values, attenuated heat transfer through the mulch, decreased soil heat flux amplitude below the mulch and reduced rates of soil water evaporation compared to inorganic mulch and bare soil.

Organic mulches better insulate landscape soils from intense solar radiation in a hot, desert climate than inorganic. Summer soil temperatures at a 5-cm depth below turf grass in an arid environment were either similar or up to 5°C lower than temperatures below ponderosa pine residue mulch. In contrast, data observed at a 1-cm soil depth in a semi-arid climate by Montague et al

(1998) found that soil temperatures below turf grass were approx. 5°C higher than below pine bark. In this study, mean diel summer soil temperatures 5-cm below the inorganic mulch, decomposing granite, were 3 to 9°C lower than beneath bare soil controls. In contrast, Li (2003) observed soil temperatures beneath gravel-sand mulch were 0.5 to 4.5°C higher than below bare soil in the semi-arid loess region of China. Pickering et al (1998) observed soil surface temperatures under bark mulch and green waste compost approx. 5°C lower than bare soil in England. Skroch et al (1992) found that organic mulches reduced maximum daily temperatures at the soil surface 2.2 to 3.3°C and increased minimum daily temperatures by 1.1 to 2.2°C in North Carolina. In comparison, in a hot, desert climate, mean maximum soil surface temperatures under the landscape tree trimming and ponderosa pine mulches were approx. 10°C to 20°C lower than bare soil. Mulch surface temperatures of pine mulch reached in excess of 60°C in both this study in a semi-arid climate in the intermountain west (Montague et al 1998). In contrast, Montague et al (1998) found that summer turf surface temperatures remained below 20°C in that same study while summer turf surface temperatures in this study reached 40°C during both years. Organic mulches, with their large pore spaces and relatively low albedo, intercept and absorb intense desert solar radiation rather than conducting heat energy directly into the soil.

Heat energy not transferred into the soil or absorbed by organic mulches can affect landscape plant physiology. Montague et al (2000) compared physiological responses of leaves of two irrigated landscape trees (*Acer plantanoides* and *Tilia cordata*) to 15-cm of pine bark and turf. Leaves growing over pine bark mulch intercepted more longwave radiation, had higher leaf temperature and greater leaf-to-air vapor pressure difference than leaves of over turf resulting in increased stomatal closure. Furthermore, Montague et al (2000) observed trees growing in turf had increased shoot elongation and leaf area than trees growing in pine bark mulch. Similar results were observed in containerized trees grown over pine bark mulch, asphalt and turf: *Malus ionensis, Acer plantanoides, Salix matsudana, Plantanus occidentalis* grown over pine bark mulch and asphalt intercepted more longwave radiation and had higher leaf temperature and leaf-to-air vapor differences than leaves on trees growing over turf resulting in lower stomatal conductance and water loss (Montague and Kjelgren, 2004). In a hot, desert climate, heat energy re-radiated into the landscape over organic and inorganic mulches did not produce significantly different temperatures at shrub canopy height. Diurnal temperatures observed at 90-cm above LTT, PPR, DG and BS surfaces were not significantly different during peak summer heat, July 2005 (Singer, data not shown).

Experimentally derived thermal conductivity for air-dried shredded landscape tree trimmings and ponderosa pine residue mulches at 38°C was determined to be 0.05 W $m^{-1}°C^{-1}$ in a completely dry system, while Montague and Kjelgren (2004) measured to the thermal conductivity of pine bark to be 0.12 W $m^{-1}°C^{-1}$ (at the time of greatest surface temperature) in a partially moist system in a semi-arid climate. These values are comparable thermal conductivity values of wood which can range from 0.055 to 0.166 W $m^{-1}°C^{-1}$, depending on the wood type (Holman, 1986). Differences between these values may be attributed to differing thermal and moisture regimes in each climate. At the landscape site used in this study, mulch and soil moisture inputs are extremely low; Montague and Kjelgren (2004) report that soil was moist at the mulch-soil interface. Soil moisture is known to effect thermal conductivity. Thermal conductivity of the mulches in this study was measured with air-dried mulches over air-dried soil because landscape surfaces mulches in the Phoenix metropolitan area are normally dry unless irrigated or penetrated by unusually heavy rains.

Landscape surface mulches affect patterns of soil heat flux. Montague and Kjelgren (2004) found that summer daytime soil heat flux under pine bark mulch was approx. 10 W m^{-2} lower than turf in a semiarid climate. In contrast, this research found that in an arid climate, summer daytime soil heat flux below turf grass was $\leq$ 5 W m^{-2} lower than below pine mulch or shredded landscape tree trimmings. In addition, the decrease in layer thickness of landscape tree trimmings over time decreased its effectiveness to intercept solar radiation during the second growing season in turn increasing soil heat flux in comparison to ponderosa pine residue mulch. The buffering capacity of decomposing granite also appeared to decrease during the second growing season compared to the first.

It is generally believed that use of mulch conserves soil moisture by reducing evaporation and increasing water infiltration (Brady and Weil, 2002) and many studies support this supposition about organic (Ashworth and Harrison, 1983; Smith and Rakow, 1992; Kraus, 1998; Pickering et al, 1998; Iles and Dosmann, 1999) and inorganic mulches (Smith and Rakow, 1992; Kraus, 1998; Iles and Dosmann, 1999; Li, 2003). Results from this study indicated that use of organic mulches over soils exposed to intense solar radiation for 21 days in a hot, desert climate can reduce soil water loss by 20- to 35-mm.

The ability of organic mulches to modify above and below ground landscape thermal environments has many implications and applications. Organic mulches can be used in the intense climate of the desert southwest to protect landscape plant rhizosphere from soil temperatures in excess of 40°C. Organic mulches also decrease the amount of heat energy that is absorbed by the soil during the day released back into the landscape at night. This raises the possibility of organic mulches being used as an urban heat island (a nighttime phenomenon in the Phoenix metropolitan area) management strategy. Although organic mulches are not the normative mulch utilized in the desert southwest, this research indicates that use of organic mulch in a hot, desert climate can be an effective landscape rhizosphere thermal management strategy. Further studies should be performed to determine how organic mulch thermal conductivity is affected by differential landscape irrigation regimes and the long term effects of organic mulches on mineral soil fertility and landscape plant physiology.

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CHAPTER 3

RESPONSES OF THREE SOUTHWEST DESERT PLANTS TO LANDSCAPE SURFACE MULCHES AND DRIP IRRIGATION

Abstract. Field research was conducted for two years to determine responses of three southwest desert plants, brittle bush (*Encelia farinosa*), four wing salt bush (*Atriplex canescens*), and blue blade cactus (*Opuntia santa rita*) to a combination of landscape mulch and drip irrigation rate treatments. All three plants were grown in field plots that were mulched (depth $\geq$ 5 cm) with shredded landscape tree trimmings, ponderosa pine residue, or decomposing granite, or not mulched (control treatment). Additionally, all *Encelia* and *Atriplex* shrubs were either drip irrigated with 2550-L or 1275-L of water per year or not irrigated after transplanting (control treatment). Landscape mulches had no affect on growth of *Atriplex* or *Encelia* shrubs. Final shoot dry mass was greatest for *Atriplex* and *Encelia* shrubs that were not irrigated. *Atriplex* had no mortality. In contrast, *Encelia* shrubs grown in the plots with either organic mulch or no mulch had about 40% and 13% mortality, respectively. *Encelia* shrubs grown in plots with decomposing mulch had no mortality. For both years, *Opuntia* cacti grown in plots with shredded landscape tree trimmings had higher padded stem relative water content than those grown in plots without mulch. These findings suggest that supplemental drip irrigation might not be needed to grow some southwest desert shrubs in local urban landscapes, and and desert shrub

response to mulches is taxa specific.

Introduction

Present concerns about rapid increases in population and limited fresh water supplies is prompting cities across the southwestern United States to encourage the landscape industry and residents to practice the principles of Xeriscape^{TM} (www.xericscape.org) including use of landscape mulches, drip irrigation, and low water use plants to foster landscape water conservation. In response to these concerns, desert landscape design and use of desert native plants in southwestern urban landscapes during the last decade has increased dramatically (Martin, 2001).

Use of mulch as a soil covering has been shown to moderate soil temperatures and lower soil water evaporation rates (Harris et al, 2004; Li, 2003; Brady and Weil, 2002; Kraus, 1998; Pickering et al, 1998; Ashworth and Harrison, 1983). Landscape surface mulches are derived from a variety of organic and inorganic parent materials and have been shown to differentially affect growth of landscape plants (Iles and Dosmann, 1999; Kraus, 1998; Foshee et al, 1996; Hild and Morgan, 1993; Holloway, 1992). For example, growth of desert willow (*Chilopsis linearis*) was improved by use of gravel and tire mulches (Kraus, 1998), but growth of five Southwest shrub species was not affected by use of pine bark mulch (Hild and Morgan, 1993).

In desert southwest urban landscapes, use of inorganic materials such as crushed rock, volcanic pumic or decomposing granite as landscape surface mulches is common. For example, municipal ordinances within the Phoenix metropolitan area stipulate exclusive use decomposing granite as a landscape surface mulch (http://phoenix.gov//ZONING/ch006.html). In contrast, landscape use of organic mulches in desert cities is uncommon, possibly because of preconceptions about the effectiveness of organic mulches under arid conditions. Recently, however, desert soils covered with organic mulches were found to have lower water evaporation rates and less amplitude in the pattern of diel temperature flucuations than did desert soils covered with inorganic mulch (Singer, Chapter 2).

Since about 1980, drip irrigation has gained wide acceptance as an effective tool to increase landscape irrigation efficiency. Well designed subsurface drip irrigation system efficiencies approach 100% (Ayars et al, 1999) compared with 85% efficiency of traditional sprinkler irrigation methods (Schneider, 2000). Landscape plants in southwest cities are normally irrigated because annual potential evapotranspiration can be as much as 10 times higher than precipitation. Though research has been done to determine irrigation requirements of some landscape plants in the Southwest (Levitt et al, 1995; Schuch and Burger, 1997; Pittenger et al, 2001; Shaw and Pittenger, 2004; Costello et al, 2005), there are no reports about the effect of drip irrigation on growth of Southwest desert native plants under landscape conditions.

Recent impetus on landscape water conservation and the recycling of forest and urban tree waste into urban landscapes has increased the need to know the combined effectiveness of different landscape mulches and drip irrigation on growth of Southwest desert native plants. Although there are numerous reports on the effect of mulches on growth of landscape plants, there is a paucity of research-based information to guide the Southwest landscape industry in use of mulches and drip irrigation under southwestern desert conditions (Borland, 1990). The objective of this research was to study the responses of three Southwest desert native plants to a combination of landscape mulch and drip irrigation rate treatments.

Materials and Methods

Research was conducted during 2004 and 2005 at an outdoor site in Phoenix, Arizona to determine responses of three Southwest desert native plants, brittle bush [*Encelia farinosa* (Torr. & A. Gray)], four wing salt bush (*Atriplex canescens* L.), and blue blade cactus [O*puntia santa rita* (Griffiths & Hare) A. Rose], to combinations of landscape mulch and drip irrigation rate treatments. Phoenix metropolitan is situated on the northeast edge of the Sonoran Desert in the southwest United States. The Phoenix region is characterized by mild, variably moist winters and intense solar radiation and extreme heat from May through September during which daytime maximum temperatures can exceed 40°C (http://www.wrh.noaa.gov/psr/). Total rainfall and potential evapotranspiration during April 2004 to October 2005 were 499-mm and 3371-mm, respectively (http://ag.arizona.edu/azmet/).

All three plants used in this field research are native to Southwest desert regions and are found in urban landscapes across the desert Southwest. *Atriplex canescens* is a Sonoran Desert native perennial shrub with an irregular habit to 2-m height with generally equal spread. *Encelia farinosa* is a mostly herbaceous, winter active perennial shrub with a rounded to spreading habit to 1.5-m height with an array of colorful yellow flowers in spring that is native to the Mojave and Sonoran Deserts. *Opuntia santa rita* is an upright and branching cactus to 1.3-m in height with rounded, purplish, padded stem segments generally about 30-cm wide having few spines and dense shortened glochids at each aerole that is native to the Chihuahuan and Sonoran Deserts.

During May 1999 an outdoor field site that consisted of 14 identical 9-m x 9-m plots was established (Stabler, 2003). Each plot contained a drip-irrigated mixture of two landscape trees and 12 shrubs and one non-irrigated *Opuntia santa rita* cactus. There was at least 1.5-m of space with no vegetation between each plot. Soil at the field site was a Rillito series gravelly loam (pH = 8.1, C = 2500 mg/kg, N = 230 mg/kg, P = 240 mg/kg) with a 0 to 1 percent slope. From 1999 to 2004, these plots had no landscape surface mulch.

During January 2004, the pre-existant shrubbery, except the *Optunia* cacti, was harvested. Two clonal *Atriplex* and four seedling *Encelia* shrubs, both in 3.8-L containers, were then transplanted into each plot at least 1.5-m apart. During April 2004, all surface debris was removed from each plot and three landscape surface mulches, shredded urban landscape tree trimmings (LTT) donated by DLC Resources (Phoenix, AZ), composted ponderosa pine residue (PPR) donated by Southwest Forest Products (Phoenix, AZ) and Red Mountain Coral decomposing granite (DG) quarried locally from the Salt River drainage were applied in a complete randomized experimental design arrangement to 12 of the plots (n = 4) to a depth of $\geq$ 5-cm. The Arizona Department of Transportation Landscape and Irrigation Specifications, Section 430.4 stipulates application of landscape mulch at a minimum depth of 5 cm.

The remaining two landscape plots did not receive any surface mulch and were considered bare soil (BS) controls. The initial physical and chemical properties of the mulches are shown in Table 3.1 (C and N content were determined by combustion method on CNS 2000 and P content was determined by dry-ash method on ICP at IAS Laboratories, Phoenix, AZ).

After transplanting, one-half of the *Atriplex* shrubs (one per plot) were subsequently drip irrigated weekly at the average rate of 2550-L water/year, an irrigation application rate that was similar to previously measured rates of drip irrigation applied to Phoenix residential landscapes (Martin, 2001). Additionally, one half of the *Encelia* shrubs were drip irrigated weekly in the following manner: one-quarter of the *Encelia* shrubs (one in each plot) were drip irrigated at the average rate of 2550-L water/year, and one-quarter of the *Encelia* shrubs (one in each plot) were drip irrigated at the average rate of 1275-L water/year. Drip irrigation rates applied to each landscape plot were recorded by totalizing water meters (Precision Meters, Orlando, FL). The remaining *Atriplex* and *Encelia* shrubs (one and two per plot, respectively) were irrigated immediately after transplanting, but received no supplemental water during both years (non-irrigated control treatment). The *Opuntia* cactus in each landscape plot received no supplemental water.

Growth of *Encelia* and *Atriplex* shrubs was evaluated in June and December 2005, respectively. Growth evaluations included measurements of plant height (h) and diameter in two directions (w_1 and w_2) after which shoots

Table 3.1. Mulch initial physical (± SE) and chemical characteristics: particle size, bulk density, carbon, nitrogen and phosphorous content, of landscape tree trimming (LTT), ponderosa pine residue (PPR) and decomposing granite (DG).

Surface mulch	Mulch particle size grade	Bulk density (g/cm^3)	C (mg/kg)	N (mg/kg)	P (mg/kg)
LTT	approx. 1.9-cm minus, un-screened	0.24 (0.08)	4.8×10^5	9.7×10^3	8.6×10^2
PPR	1.9-cm minus, screened	0.25 (0.08)	5.4×10^5	1.5×10^3	6.4×10^1
DG	0.6-cm minus, screened	1.69 (0.07)	2.4×10^3	6.6×10^1	7.3×10^1

were harvested, dried at 65°C for 72 hrs and weighed. A growth index (GI) was calculated for each shrub as:

$$GI = (h+w_1+w_2)/3$$

Counts of shrub mortality for both shrub taxa were made when shoots were harvested.

Evaluations of percent RWC of *Atriplex* leaves were made seasonally during the spring, summer and fall of 2004 and 2005. Evaluations of percent RWC of *Opunita* padded stem segments were made only during the fall of each year instead of seasonally due to the limited number of padded stem segments on each cactus. To determine percent RWC, three recently physiologically mature leaves or padded stem segments per plant were harvested at dawn. Leaves or padded stems segments were then weighed as soon as possible for an initial fresh mass after harvest (FM). Leaves or padded stem segments were then floated in water for 24-hr (48 hrs for *Opuntia* pads) at room temperature and weighed for fully turgid mass (SM). Finally, leaves or padded stem segments were dried at 65^{o}C (*Atriplex* leaves for 72-hr; *Opuntia* stem segments for 28 days) and weighed for dry mass (DM). Percent leaf RWC was calculated according to the formula (Jiang and Huang, 2001):

$$RWC = (FM-DM) / (SM-DM) X 100.$$

No evaluations of *Encelia* leaf RWC were made because leaf surfaces of this shrub are highly tomentose and resistant to forced hydration.

Volumetric soil water content was recorded monthly during March to June 2005 in all 14 plots using a Field Scout TDR 100 soil moisture probe (Spectrum Technologies, Plainfield, IL) after an unseasonably wet winter brought 232.7-mm of rain from November 2004 to February 2005; during March to June 2005 15.5-mm of rain fell (http://ag.arizona.edu/azmet/). The moisture probe was inserted vertically into only non-irrigated soils to a depth of 12-cm. Nine measurements were made per plot in three north-south transects.

Data analysis. Experimental design varied by research question and treatment structure. A two-factor split plot design was used in analysis of the effects of landscape surface mulches (whole unit) and irrigation (subunit) treatments on dependent variable responses of *Atriplex* and *Encelia*. The whole units were arranged in a completely randomized design structure. The subunits were arranged in an incomplete block design structure with levels of irrigation randomly assigned within mulched landscape plots. Where drip irrigation was not applied, a completely randomized design structure was used in analysis of the effects of landscape mulches on *Opuntia* padded stem segment RWC and unirrigated soil VWC.

An analysis of variance (ANOVA) was calculated for all data using a general linear model (JMP 5.0.1, SAS Institute Inc, 2002). A two-way multivariate model with surface mulch treatment, irrigation treatment and the interaction of mulch and irrigation treatments as independent variables was used for statistical comparisons of *Atriplex* leaf RWC as well as *Atriplex* and

Encelia growth index and shoot dry mass. A one-way univariate model with landscape mulch type as the independent variable was used for statistical comparisons of *Opuntia* padded stem segment RWC and soil VWC. If significantly different ($P \leq 0.05$), then dependent variable mean values were separated using Tukey's HSD multiple comparisons test ($\alpha = 0.05$).

Results

Mean final growth index for *Atriplex* shrubs was not significantly different by mulch type, irrigation or interaction of treatments (Table 3.2). However, mean *Atriplex* total shoot dry mass was greatest in shrubs growing in non-irrigated locations (P = 0.0364, Table 3.2) but not significantly different by mulch treatment or interaction of treatments (Table 3.2).

Mean final growth for *Encelia* shrubs was greatest for shrubs that were not irrigated (P = 0.0001, Table 3.3), but growth was not affected by mulch treatment or interaction of treatments (Table 3.3). Furthermore, mean *Encelia* shoot dry mass was greatest in shrubs growing in non-irrigated locations (P = 0.0005, Table 3.3) although not significantly different by mulch treatment or interaction of treatments (Table 3.3); mean shoot dry mass was not significantly different between the two irrigation levels (Table 3.3).

No *Atriplex* shrubs died during this study. In addition, none of the *Encelia* shrubs grown in DG mulch died. Thirteen percent of the *Encelia* shrubs grown in BS died. *Encelia* shrubs grown in organic treatments had the highest percentage of mortality; shrubs grown in PPR and LTT experienced 44% and 38% mortality, respectively. *Encelia* shrubs irrigated at rates of 2550-L/year and 1275-L/year both experienced 36% mortality. Fourteen percent of non-irrigated *Encelia* shrubs died.

Table 3.2. Effect of drip irrigation rate on mean final harvest growth index [(h + w_1 + w_2)/3] and total shoot dry mass of *Atriplex canescens*.

Irrigation (L/plant/year)	Growth index (m)	Shoot mass (kg)
2550	0.90[z] a[y]	0.61 b
0	1.12 a	1.13 a

[z] Values are treatment means, n = 14.

[y] Mean values within the same column followed by the same letter were not significantly different, using Tukey's HSD test ($\alpha = 0.05$).

Table 3.3. Effect of drip irrigation rate on mean final harvest growth index [(h + w_1 + w_2)/3] and total shoot dry mass of *Encelia farinosa*.

Irrigation (L/plant/year)	Growth index (m)	Shoot mass (kg)
2550	0.63 b	0.43 b
1275	0.59 b	0.26 b
0	0.98 a	0.77 a

[z] Values are treatment means, n=14 except for non-irrigated plants where n = 28.

[y] Mean values within the same column followed by the same letter were not significantly different, using Tukey's HSD test (α = 0.05).

Atriplex mean percent leaf RWC was significantly different by the interaction of mulch and irrigation treatments during both years (Tables 3.4 & 3.5). During spring and summer 2004 mean percent leaf RWC was higher in BS, non- irrigated plants compared to BS irrigated plants (Table 3.4). During fall 2004 mean percent leaf RWC was significantly different by irrigation in PPR and DG. In PPR mean percent leaf RWC was highest in irrigated plants and in DG mean percent leaf RWC was highest in non-irrigated plants (Table 3.4). One year after mulch installation mean percent leaf RWC was significantly higher in non-irrigated growing in DG compared to irrigated plants (Table 3.5). During summer and fall 2005, mean percent leaf RWC was different by irrigation in PPR, DG and BS treatments. In PPR mean percent leaf RWC was highest in irrigated plants; in contrast, mean percent leaf RWC was highest in non-irrigated plants in DG and BS (Table 3.5).

At the end of the first year after the application of landscape surface mulches mean percent RWC of *Opuntia* padded stem segments was not significantly different by mulch treatment (P = 0.1025, Table 3.6). By the end of the second year after being treated with landscape surface mulches, however, plants growing in LTT had significantly higher padded stem segment percent RWC than plants growing in BS, although not significantly different from plants growing in PPR and DG (P = 0.0047, Table 3.6).

Soil percent VWC was generally higher beneath mulched surfaces than BS (Table 3.7). After the winter rains of 2005, soil moisture was higher under

Table 3.4. Effect of landscape mulch and irrigation treatments on mean percent leaf relative water content (RWC) of *Atriplex canescens* during April, July and October 2004. Landscape mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG) and bare soil (BS). Irrigation treatments were 2550 L/plant/year and no supplemental irrigation.

		Atriplex leaf RWC (%)		
Mulch	Irrigation (L/plant/year)	Apr	Jul	Oct
LTT	2550	77.9[z] a[y]	66.7 a	81.8 a
LTT	0	79.7 a	61.5 a	81.1 a
PPR	2550	75.3 a	66.4 a	81.9 a
PPR	0	70.2 a	60.2 a	71.9 b
DG	2550	75.9 a	69.4 a	73.1 b
DG	0	77.7 a	66.4 a	84.6 a
BS	2550	67.7 b	59.7 b	80.6 a
BS	0	80.8 a	74.3 a	82.7 a
P-values				
Mulch		0.0346	0.2169	0.2743
Irrigation		0.0898	0.9894	0.7333
Mulch*Irrigation		0.0096	0.0026	0.0011

[z] Values are treatment means, LTT, PPR, DG n = 12; BS n = 6.

[y] Mean values within the same column followed by the same letter were not significantly different for irrigation treatment by mulch treatment using Student's t-test ($\alpha = 0.05$).

Table 3.5. Effect of landscape mulch and irrigation treatments on mean percent leaf relative water content (RWC) of *Atriplex canescens* during April, August and October 2005. Landscape mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG) and bare soil (BS). Irrigation treatments were 2550 L/plant/year and no supplemental irrigation.

		Atriplex leaf RWC (%)		
Mulch	Irrigation (L/plant/year)	Apr	Aug	Oct
LTT	2550	79.4^{z} a^{y}	66.8 a	67.5 a
LTT	0	76.6 a	67.4 a	68.8 a
PPR	2550	76.3 a	67.0 a	71.9 a
PPR	0	77.5 a	60.1 b	62.7 b
DG	2550	67.4 b	62.2 b	64.8 b
DG	0	74.6 a	70.8 a	78.5 a
BS	2550	75.9 a	62.5 b	67.3 b
BS	0	71.0 a	76.8 a	81.3 a
P-values				
Mulch		<0.0001	0.1987	0.0727
Irrigation		0.8728	0.0046	0.0143
Mulch*Irrigation		0.0012	0.0008	<0.0001

^{z}Values are treatment means, LTT, PPR, DG n = 12; BS n = 6.

^{y}Mean values within the same column followed by the same letter were not significantly different for irrigation treatment by mulch treatment using Student's t-test (α = 0.05).

Table 3.6. Effect of landscape mulch treatment on mean padded stem segment percent relative water content (RWC) of *Opuntia santa rita* during November of 2004 and 2005. Landscape mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG), and bare soil (BS).

	Padded stem segment RWC (%)	
Mulch	2004	2005
LTT	87.1[z] a[y]	89.7 a
PPR	87.3 a	86.0 ab
DG	84.6 a	83.3 ab
BS	80.7 a	76.3 b

[z] Values are treatment means; LTT, PPR, DG n=12, BS n=6.

[y] Mean values within the same column followed by the same letter were not significantly different, using Tukey's HSD test ($\alpha = 0.05$).

Table 3.7. Effect of landscape mulch treatment on mean soil volumetric water content, March to June 2005. Landscape mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG), and bare soil (BS).

	VWC (%)			
Mulch	Mar	Apr	May	Jun
LTT	20[z] a[y]	16 a	11 a	7 ab
PPR	20 a	15 a	11 a	6 b
DG	17 b	15 a	12 a	7 a
BS	14 b	10 b	9 b	6 b

[z] Values are treatment means; LTT, PPR, DG n=36, BS n=18.

[y] Mean values within the same column followed by the same letter were not significantly different, using Tukey's HSD test ($\alpha = 0.05$).

LTT and PPR mulches compared to DG and BS (P = 0.0003, Table 3.7). During April and May 2005 soil moisture was higher beneath all mulched surfaces compared to BS (P = 0.0048, P = 0.0002, Table 3.7). By June 2005 soil moisture continued to be significantly different by treatment although percent VWC was extremely low across all treatments (P = 0.0030, Table 3.7).

Discussion

It is generally accepted that use of mulch increases soil moisture by reducing evaporation and increasing water infiltration (Brady and Weil, 2002) and many studies support this supposition about organic (Ashworth and Harrison, 1983; Smith and Rakow, 1992; Kraus, 1998; Pickering et al, 1998; Iles and Dosmann, 1999) and inorganic mulches (Smith and Rakow, 1992; Kraus, 1998; Iles and Dosmann, 1999; Li, 2003). However, in the urban desert landscape mulches conserve soil moisture only if usually light desert rains can penetrate the mulch layer or irrigation is used in the landscape.

Landscape surface mulches are thought to benefit the growth of plants by buffering roots from soil temperature extremes and increasing water availability. Use of inorganic mulches has been shown to increase stem caliper and leaf dry mass of Red Flame® maple trees compared to trees grown in shredded bark (Iles and Dosmann, 1999) and use of organic mulches has been shown to increase growth of young pecan trees (Foshee et al 1996). However, the benefits of landscape surface mulches to landscape plants are mulch and taxa specific. Studies have shown that inorganic and organic mulches can differentially affect growth and water relations of some landscape plants. After two growing seasons, desert willow trees (*Chilopsis linearis*) grown in inorganic mulches had greater shoot dry weight than those grown in organic mulch (Kraus, 1998). *Fraxinus pennsylvanica* 'Emerald' grown in shredded bark had less negative water potentials compared to those grown in gravel, wood chips, fine bark and bare soil (Smith and Rakow, 1992). Sometimes mulch does not affect the growth of plants. Hild and Morgan (1993) found that pine bark mulching did not affect the growth of five southwestern shrub species.

Research was conducted to determine the effects of organic and inorganic surface mulches and differential drip-irrigation rates on growth and mortality of *Atriplex canescens*, and *Encelia farinosa* shrubs, relative water content of *Atriplex canescen*s leaves and *Opuntia santa rita* padded stem segments and landscape soil VWC. Results of this study showed that these three landscape plants, indigenous to Southwest deserts, respond uniquely to the moisture and thermal regimes of different mulch types. *Atriplex* shrubs generally had higher leaf RWC growing in bare soil and decomposing granite while *Opuntia* padded stem segments had higher RWC when growing in landscape tree trimmings. Furthermore, *Encelia* shrub growth was not affected by mulch type, but *Encelia* shrubs underwent the highest mortality rates in organic mulches while *Atriplex* shrubs experienced no mortality during two growing seasons. Furthermore, highest *Encelia* percent mortality was observed in irrigated shrubs, regardless of irrigation application rate (2550 L/year and 1275 L/year).

In an effort to conserve water in the urban desert, many municipalities in the Phoenix area encourage residents to limit water use by installing drip irrigation systems and planting low-water use plants and indigenous plants adapted to harsh desert conditions. Furthermore, principles of Xeriscape^{TM} (www.xeriscape.org) prescribe use of mulches in the landscape to reduce soil water evaporation and soil temperatures and efficient irrigation to promote water conservation. The findings in this study suggest that benefits of organic mulches in the landscape are taxa specific. More studies need to be performed to examine how organic mulches affect the growth and relative water content of other commonly used native and exotic plants in xeric, southwest landscapes. Research also needs to be done to determine the ability of organic mulches to transmit and foster plant pathogens that might in turn cause taxa-specific mulch mortality.

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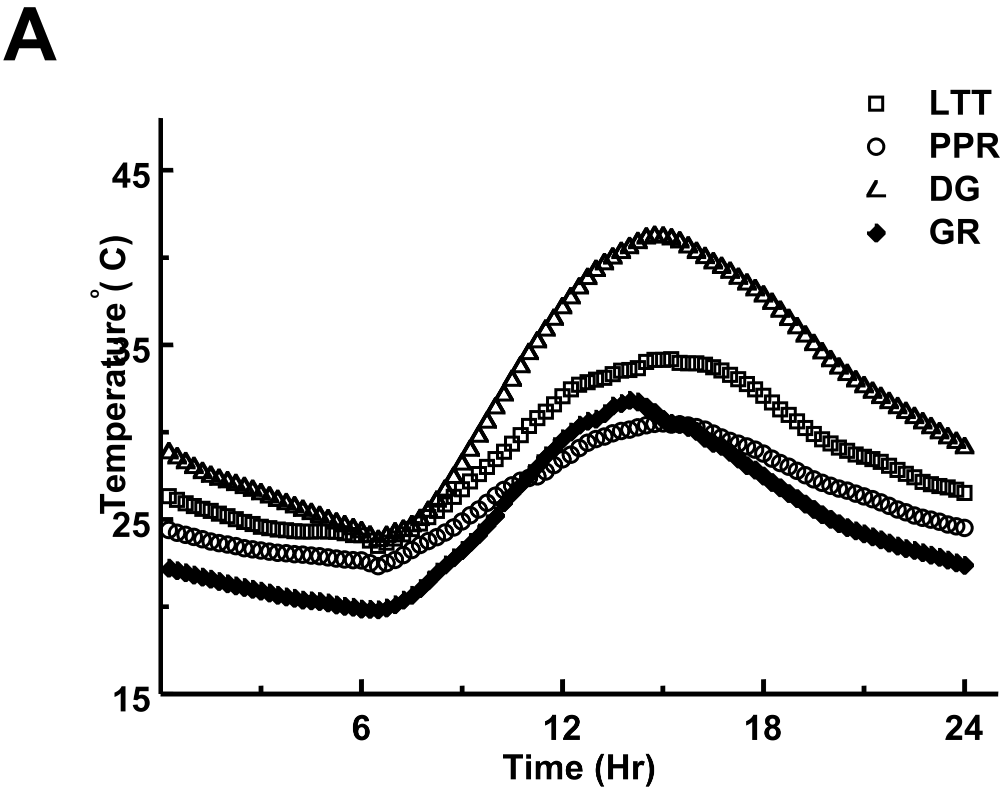
APPENDIX A

ABIOTIC DESERT LANDSCAPE MICROCLIMATE RESPONSES TO LANDSCAPE SURFACE MULCHES


A
LTT
PPR
DG
GR
Temperature °(C)
45
35
25
15
6
12
18
24
Time (Hr)

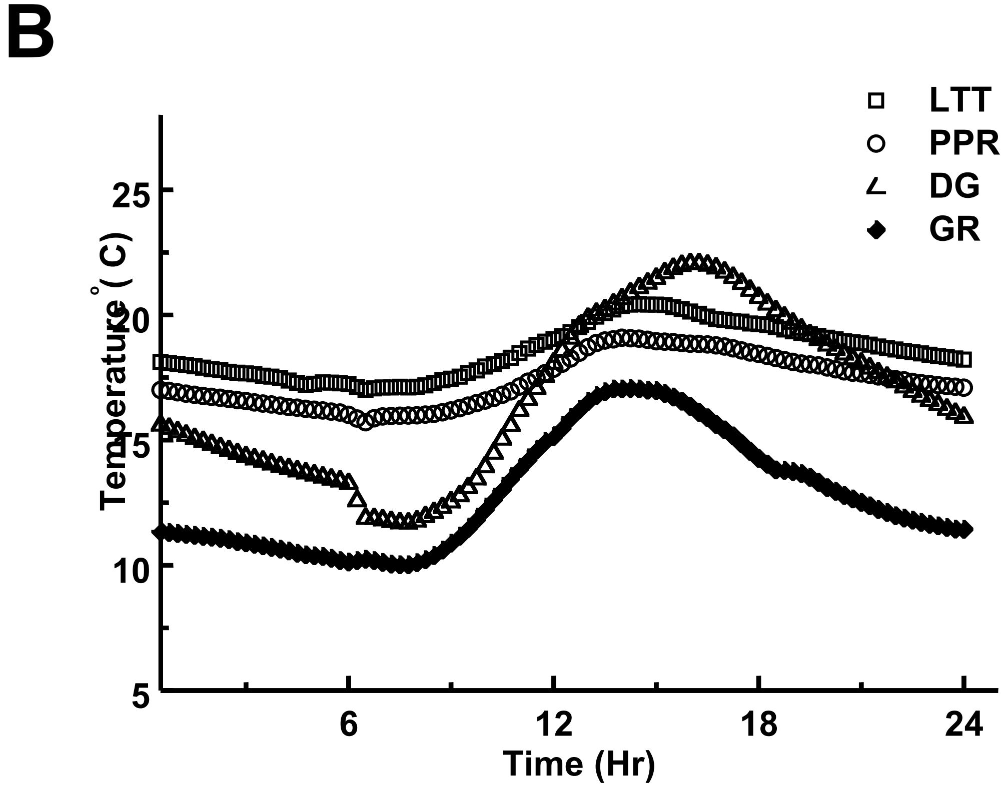
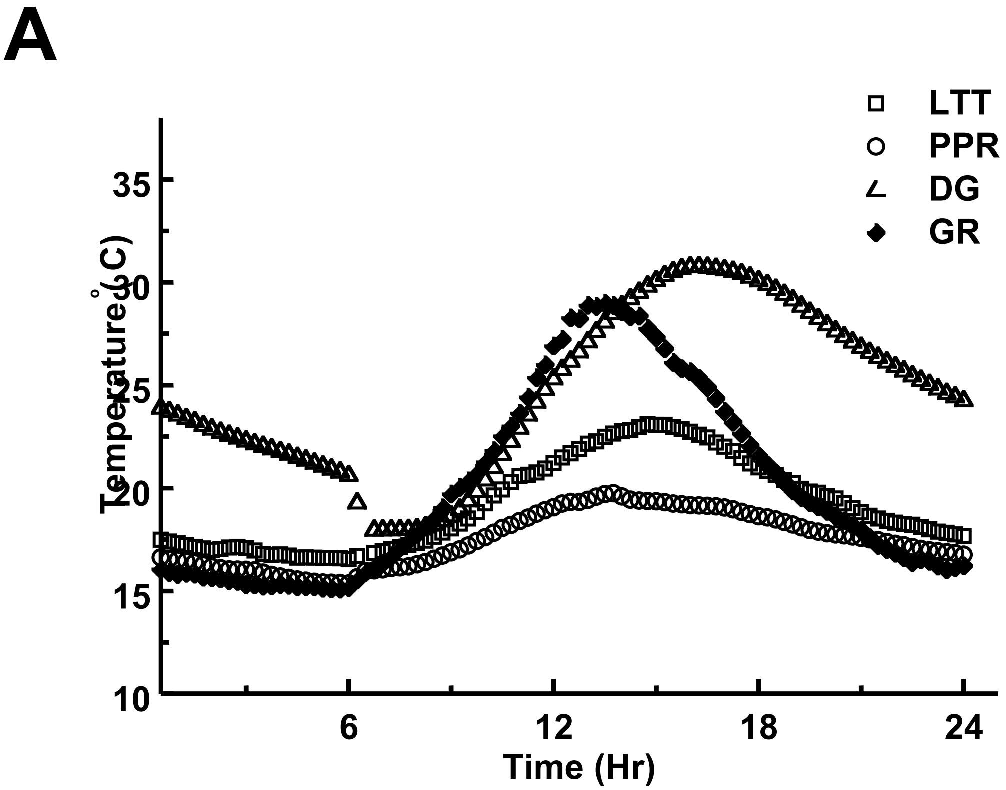

B
LTT
PPR
DG
GR
Temperature °(C)
25
20
15
10
5
6
12
18
24
Time (Hr)

Figure A.1. Effect of landscape surface mulch treatments on mean diel soil surface temperatures beneath mulch and turf grass during: A) May 2004 and B) November 2004. Landscape surface mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG) and turf (GR). Values are treatment means (LTT, PPR, DG n = 4 and GR n = 2).


A
LTT
PPR
DG
GR
Temperature (°C)
35
30
25
20
15
10
6
12
18
24
Time (Hr)

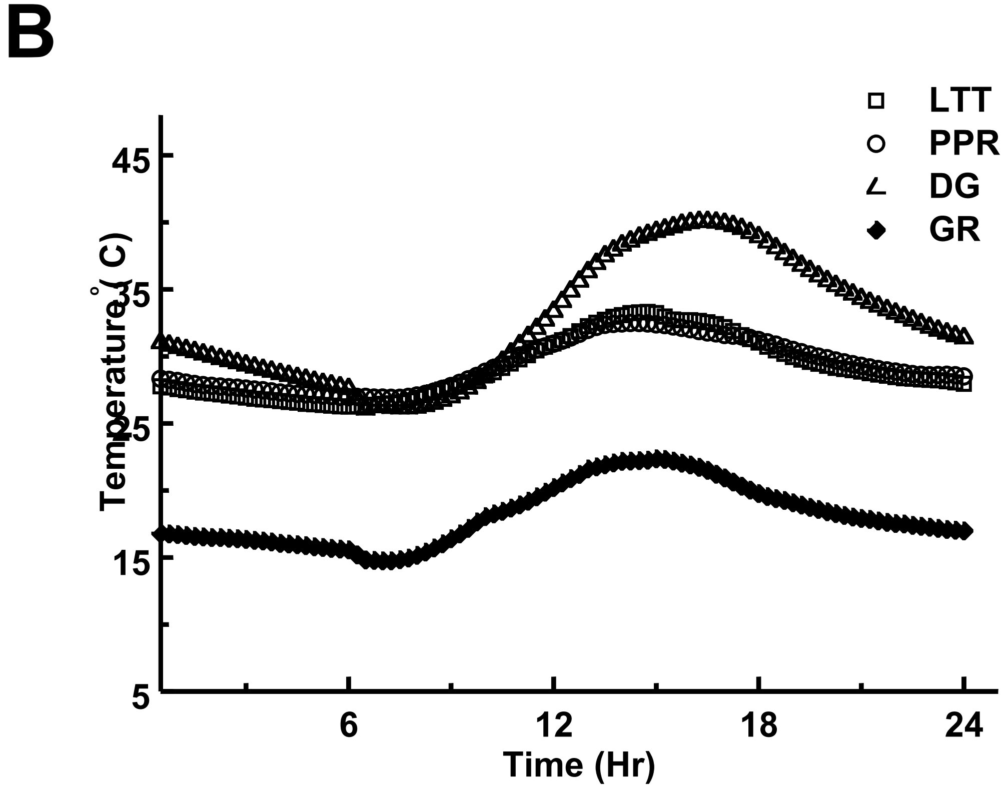

B
LTT
PPR
DG
GR
Temperature (°C)
45
35
25
15
5
6
12
18
24
Time (Hr)

Figure A.2. Effect of landscape surface mulch treatments on mean diel soil surface temperatures beneath mulch and turf grass during: A) April 2005 and B) October 2005. Landscape surface mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG) and turf (GR). Values are treatment means (LTT, PPR, DG n = 4 and GR n = 2).

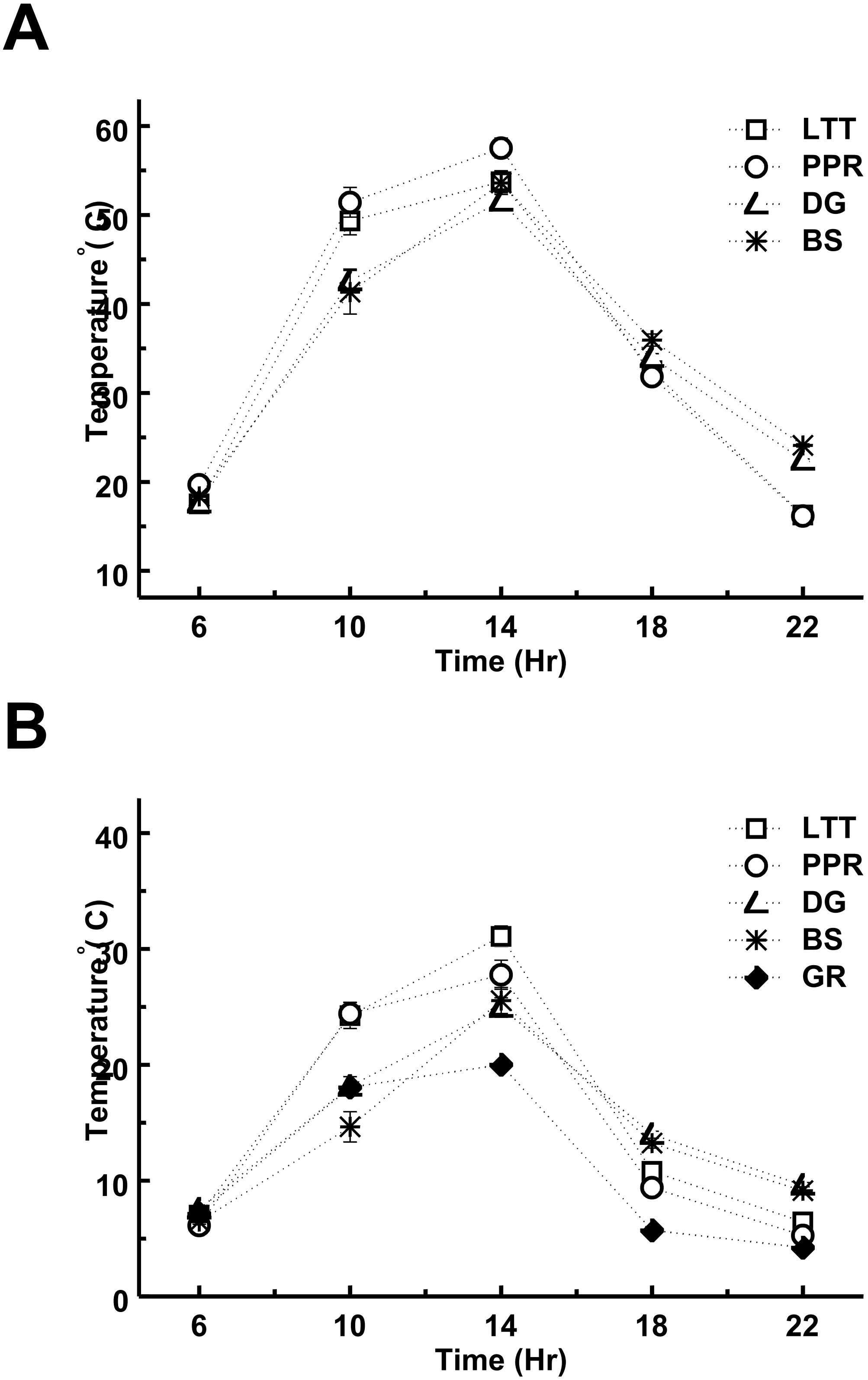

A
Temperature (°C)
60
50
40
30
20
10
6
10
14
18
22
Time (Hr)
LTT
PPR
DG
BS
B
Temperature (°C)
40
30
20
10
0
6
10
14
18
22
Time (Hr)
LTT
PPR
DG
BS
GR

Figure A.3. Effect of landscape surface mulch treatments on mean diel landscape surface temperatures during: A) May 2004 and B) November 2004. Landscape surface mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG), turf (GR) and bare soil (BS). Values are treatment means (LTT, PPR, DG n = 36 and GR, BS n = 18); vertical lines represent ± SE of the means; where not visible ± SE is smaller than symbol size.

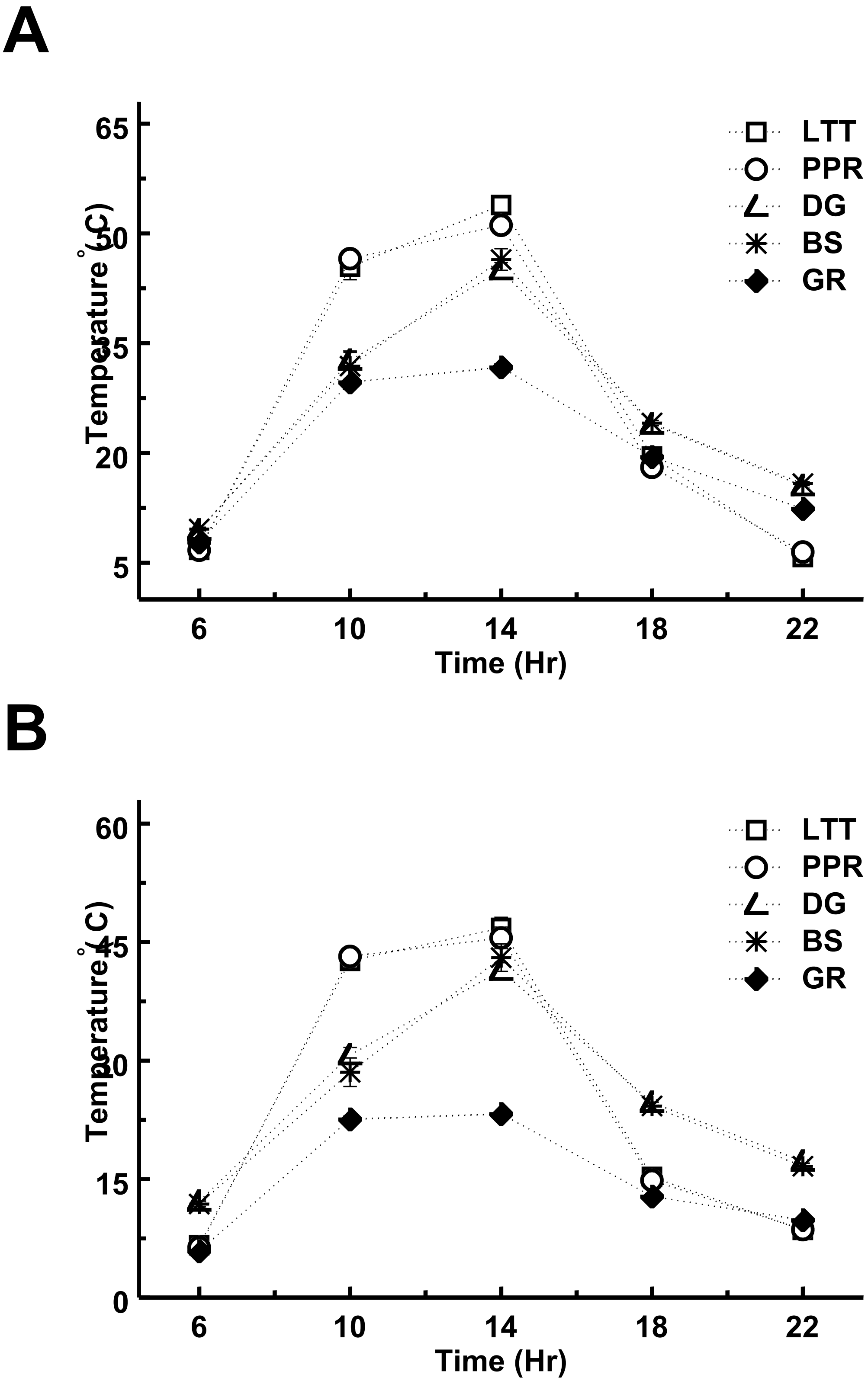

A
Temperature °C)
65
50
35
20
5
6
10
14
18
22
Time (Hr)
LTT
PPR
DG
BS
GR
B
Temperature °C)
60
45
30
15
0
6
10
14
18
22
Time (Hr)
LTT
PPR
DG
BS
GR

Figure A.4. Effect of landscape surface mulch treatments on mean diel landscape surface temperatures during: A) April 2005 and B) October 2005. Landscape surface mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG), turf (GR) and bare soil (BS). Values are treatment means (LTT, PPR, DG n = 36 and GR, BS n = 18); vertical lines represent ± SE of the means; where not visible ± SE is smaller than symbol size.

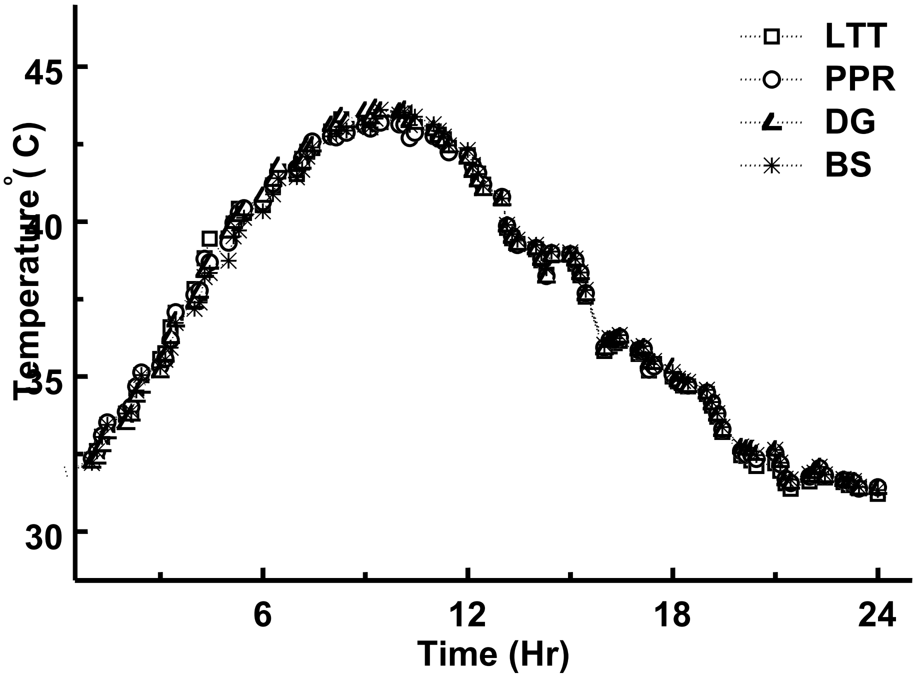

Temperature °(C)
45
40
35
30
6
12
18
24
Time (Hr)
LTT
PPR
DG
BS

Figure A.5. Effect of landscape surface mulches on ambient air temperatures 90-cm above the landscape surface during July 2005. Landscape surface mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG) and bare soil (BS). Values are treatment means (n = 2).

Table A.1. Mean integrated net radiation values (MJ/m^2) over landscape tree trimmings (LTT), ponderosa pine residue (PPR), turf (GR), decomposing granite (DG) and bare soil (BS) by day (0600 to 1800 HR) and night (1800 to 0600 HR) during May and November 2004.

	Net Radiation (MJ/m^2)			
	May		Nov	
Treatment	Day	Night	Day	Night
LTT	12.92[z] b[y]	-2.04 a	5.78 a	-1.52 a
PPR	13.16 b	-2.00 a	4.85 a	-1.60 a
GR	17.35 a	-1.90 a	5.49 a	-1.39 a
DG	10.93 b	-3.16 b	4.97 a	-2.70 b
BS	14.16 ab	-3.44 b	5.00 a	-2.34 ab

[z] Values are treatment means, n = 4.

[y] Mean values within the same column followed by the same letter were not significantly different, using Tukey’s HSD test (α = 0.05).

Table A.2. Mean integrated net radiation values (MJ/m^2) over landscape tree trimmings (LTT), ponderosa pine residue (PPR), turf (GR), decomposing granite (DG) and bare soil (BS) by day (0600 to 1800 HR) and night (1800 to 0600 HR) during April and October 2005.

	Net Radiation (MJ/m^2)			
	Apr		Oct	
Treatment	Day	Night	Day	Night
LTT	12.44^{z}b^y	-1.71 a	8.19 a	-1.73 a
PPR	9.84 b	-1.69 a	7.31 a	-1.66 a
GR	16.32 a	-1.88 a	7.74 a	-2.25 ab
DG	10.26 b	-2.89 b	6.14 a	-2.53 b
BS	9.84 ab	-2.85 b	5.96 a	-2.80 b

[z] Values are treatment means, n = 4.

[y] Mean values within the same column followed by the same letter were not significantly different, using Tukey's HSD test ($\alpha = 0.05$).

Table A.3. Effect of landscape surface mulches on mean EC and pH of soil surrounding drip-irrigated *Nerium oleander* shrubs (saturated paste method). Soil cores (20-cm depth) were taken at distances of 0-, 0.5-, 1.0- and 1.5-m from *Nerium* shrubs below surface mulches during September 2005. Landscape surface mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG) and bare soil control (BS).

Mulch	EC (dS/m)	pH	Distance	EC (dS/m)	pH
LTT	1.46^{z}a^{y}	8.10 a	0	1.76 b	8.10 a
PPR	1.53 a	8.10 a	0.5	3.55 a	8.10 a
DG	1.53 a	8.15 a	1.0	0.71 b	8.17 a
BS	2.21 a	8.11 a	1.5	0.71 b	8.14 a

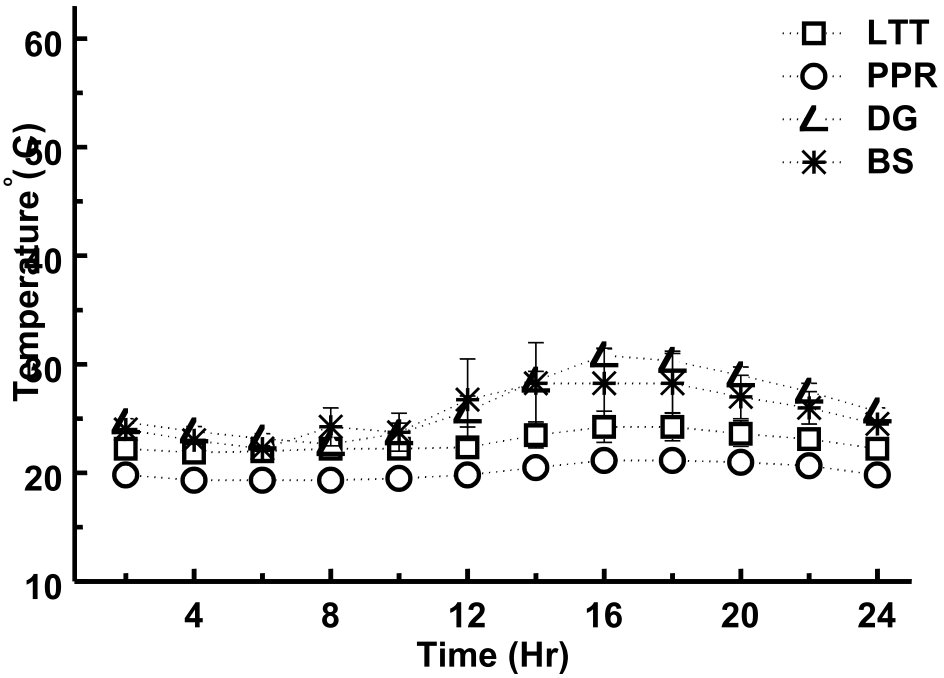
[z] Values are treatment means, n = 12.

[y] Mean values within the same column followed by the same letter were not significantly different, using Tukey’s HSD test ($\alpha = 0.05$).

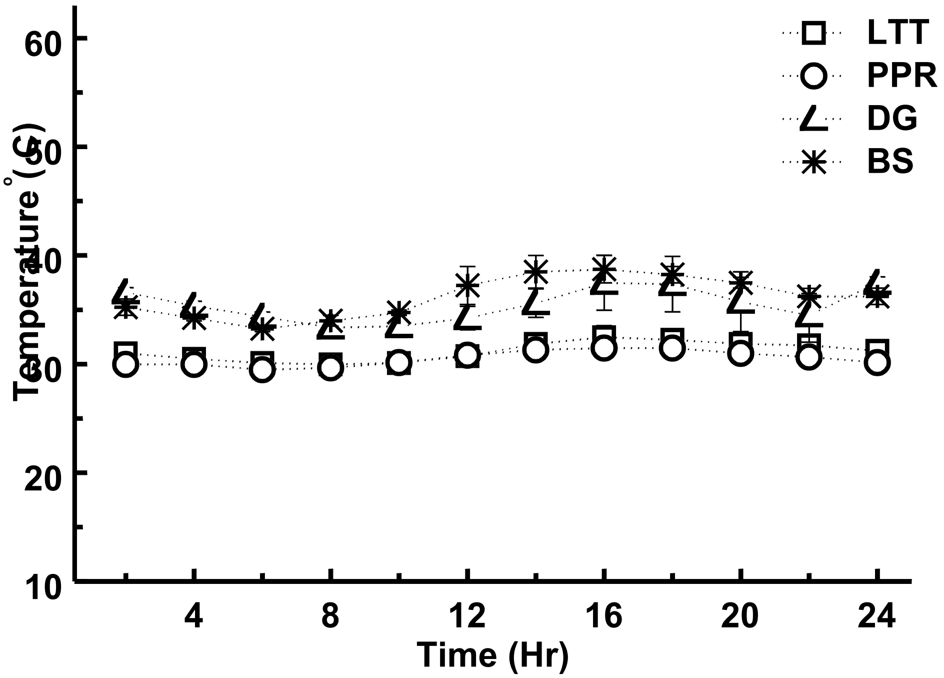
APPENDIX B

BIOTIC LANDSCAPE AND DESERT PLANT RESPONSES TO LANDSCAPE SURFACE MULCHES

A


Temperature °C
60
50
40
30
20
10
4
8
12
16
20
24
Time (Hr)
LTT
PPR
DG
BS

B


Temperature °C
60
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40
30
20
10
4
8
12
16
20
24
Time (Hr)
LTT
PPR
DG
BS

C

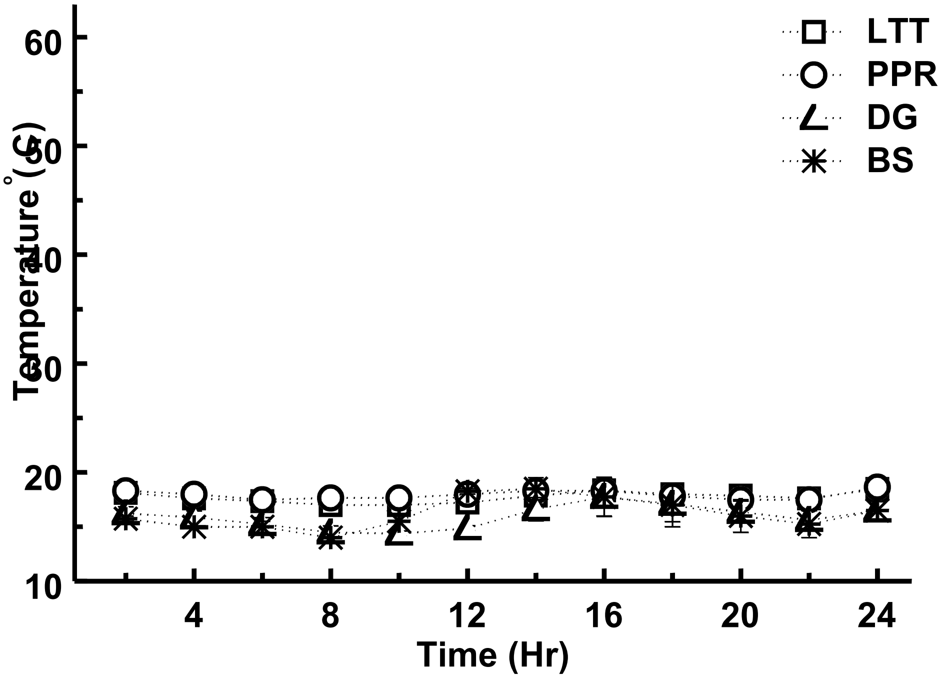
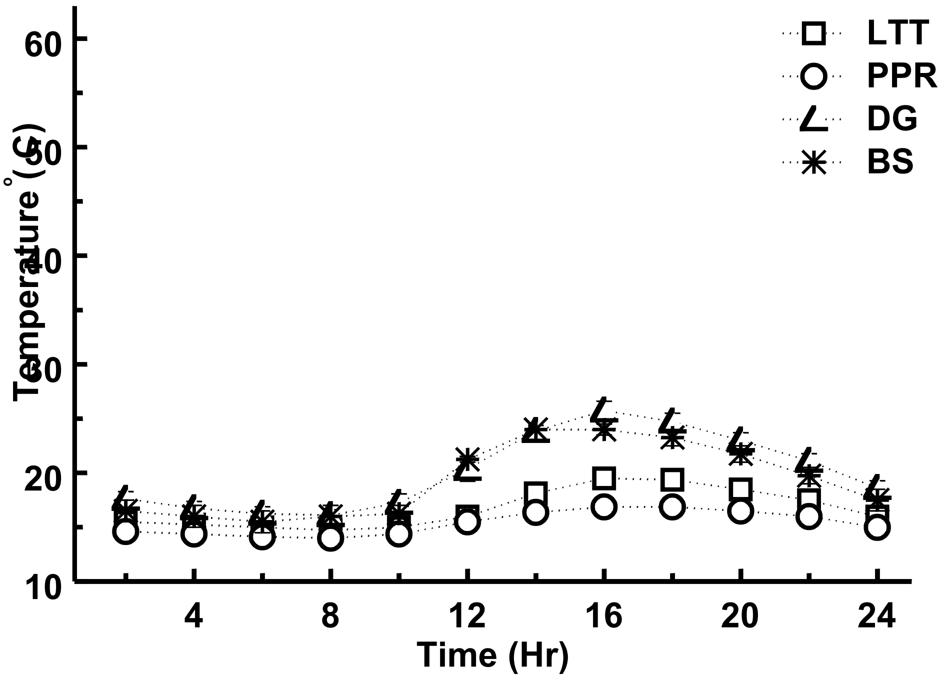

60
50
40
30
20
10
Temperature °(C)
4
8
12
16
20
24
Time (Hr)
□ LTT
○ PPR
∠ DG
✳ BS

Figure B.1. Effect of landscape surface mulch treatments on mean diel soil temperatures under *Nerium oleander* shrub canopy at a 5-cm depth during: A) May, B) August and C) November 2004. Landscape surface mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG) and bare soil (BS). Values are treatment means (LTT, PPR, DG n = 4 and BS n = 2); vertical lines represent ± SE of the means; where not visible ± SE is smaller than symbol size.

A


LTT
PPR
DG
BS
Temperature °C
60
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40
30
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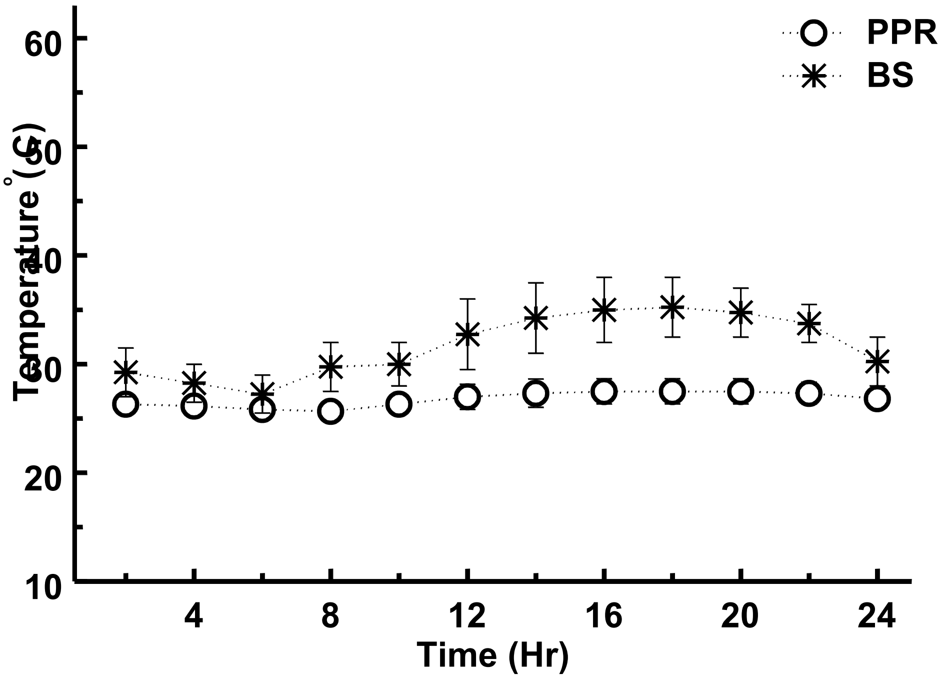
10
4
8
12
16
20
24
Time (Hr)

B


PPR
BS
Temperature °C
60
50
40
30
20
10
4
8
12
16
20
24
Time (Hr)

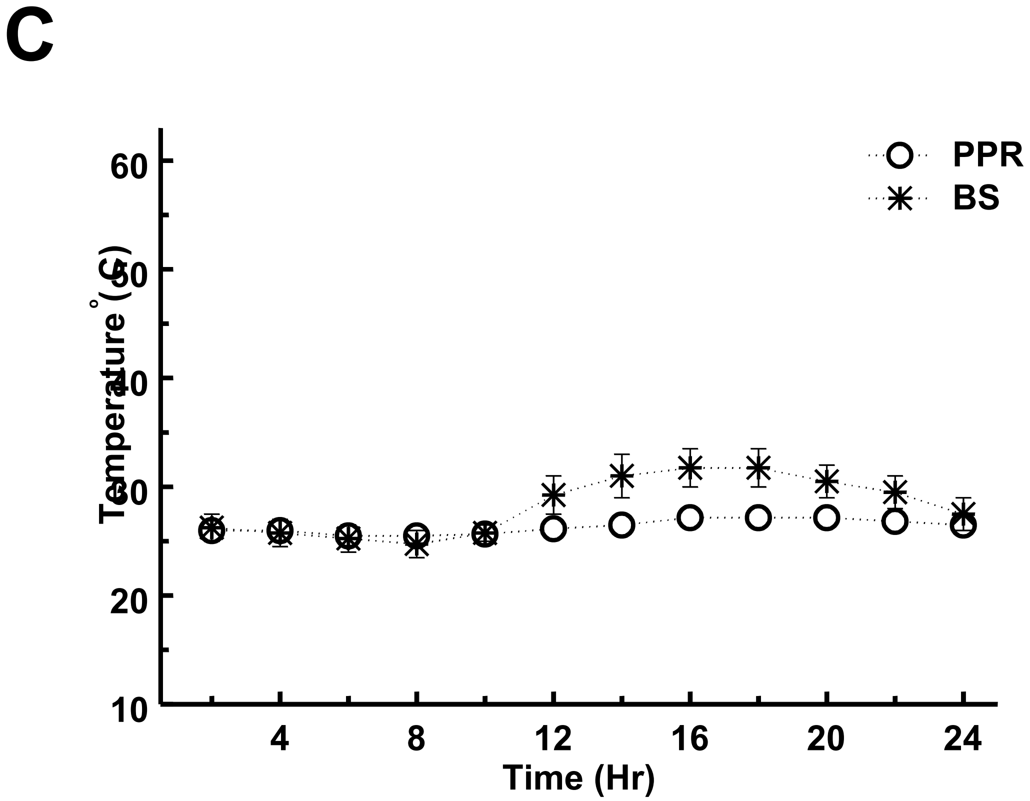
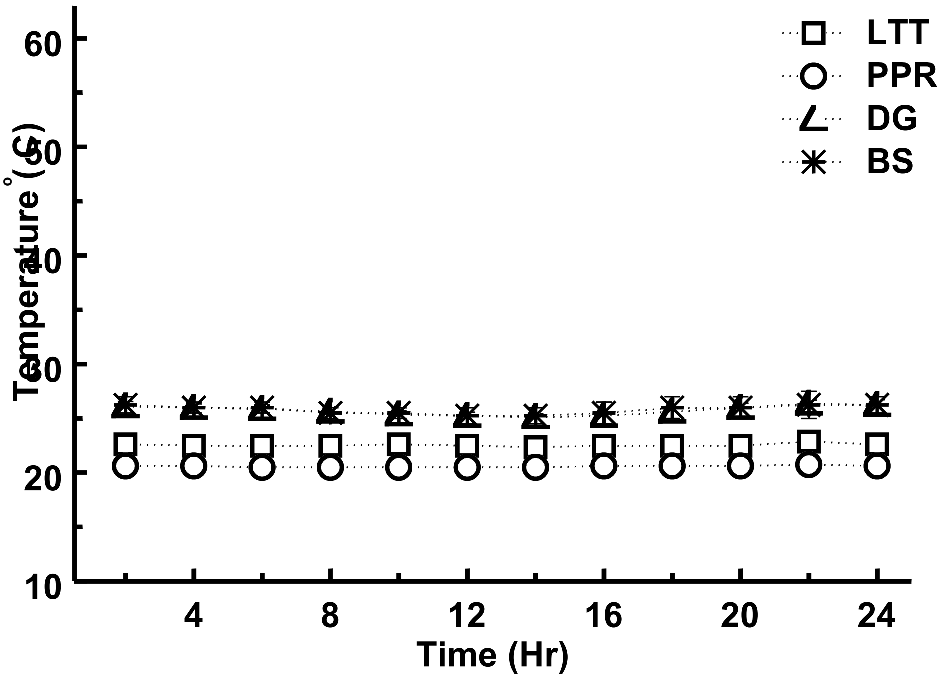
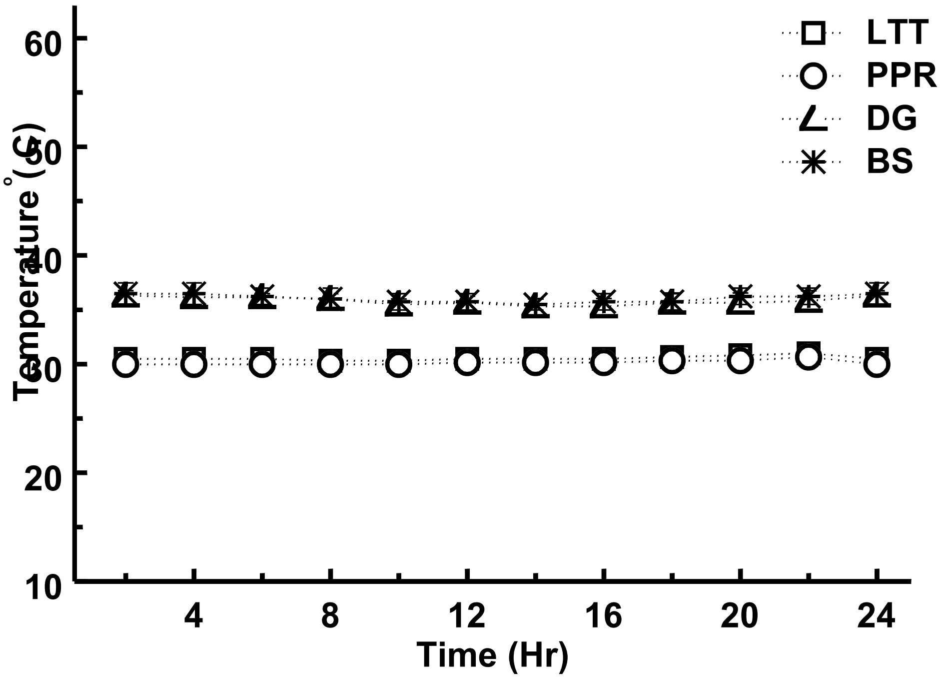

C
PPR
BS
Temperature °(C)
60
50
40
30
20
10
4
8
12
16
20
24
Time (Hr)

Figure B.2. Effect of landscape surface mulch treatments on mean diel soil temperatures under *Nerium oleander* shrub canopy at a 5-cm depth during: A) April, B) July and C) October 2005. Landscape surface mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG) and bare soil (BS). Values are treatment means (LTT, PPR, DG n = 4 and BS n = 2); vertical lines represent ± SE of the means; where not visible ± SE is smaller than symbol size.

A


Temperature °C
60
50
40
30
20
10
4
8
12
16
20
24
Time (Hr)
LTT
PPR
DG
BS

B


Temperature °C
60
50
40
30
20
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4
8
12
16
20
24
Time (Hr)
LTT
PPR
DG
BS

C

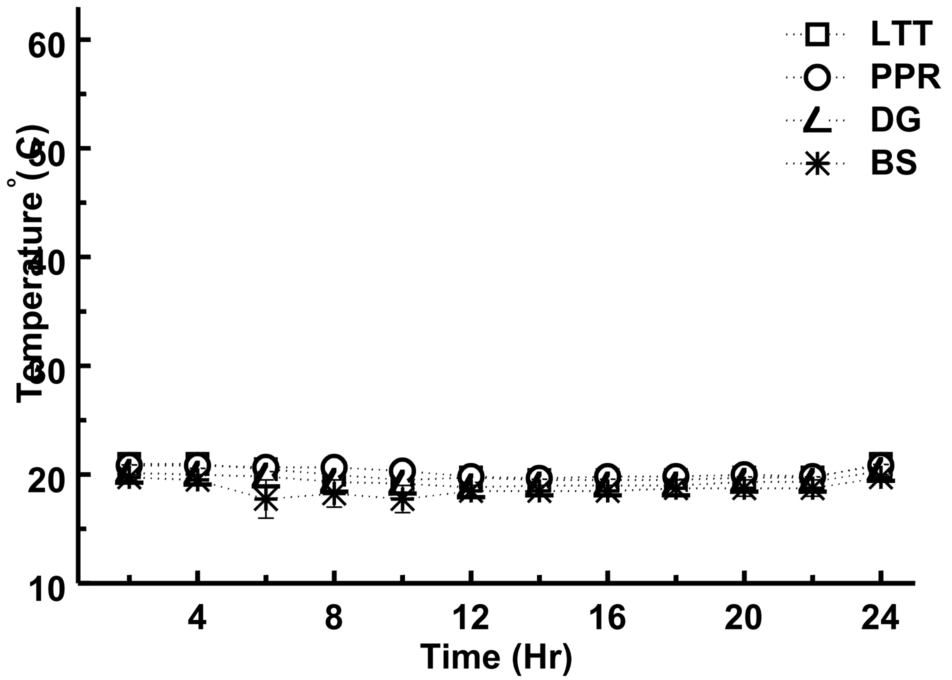
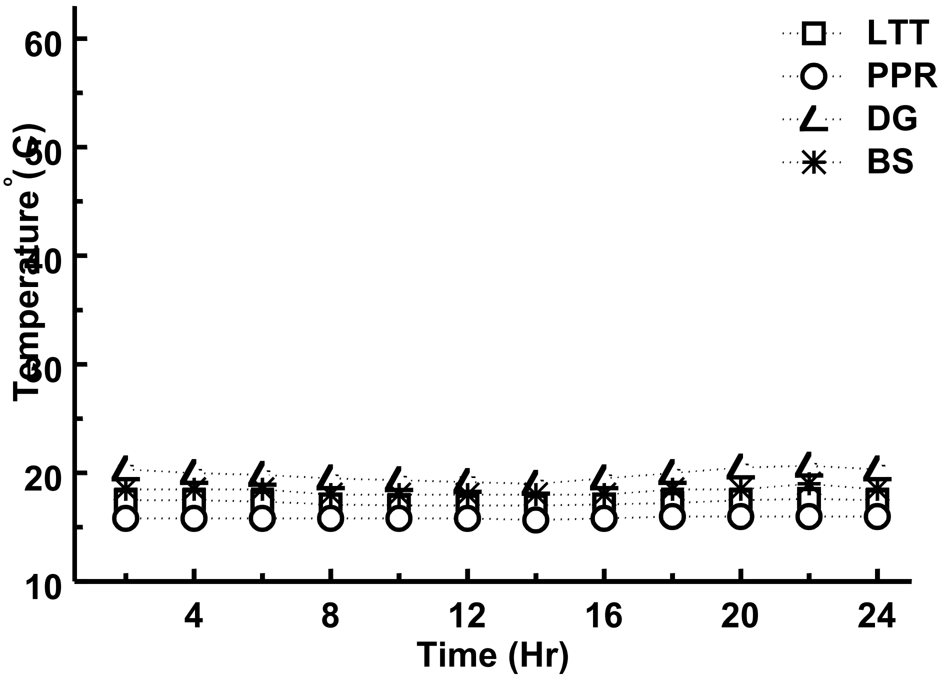
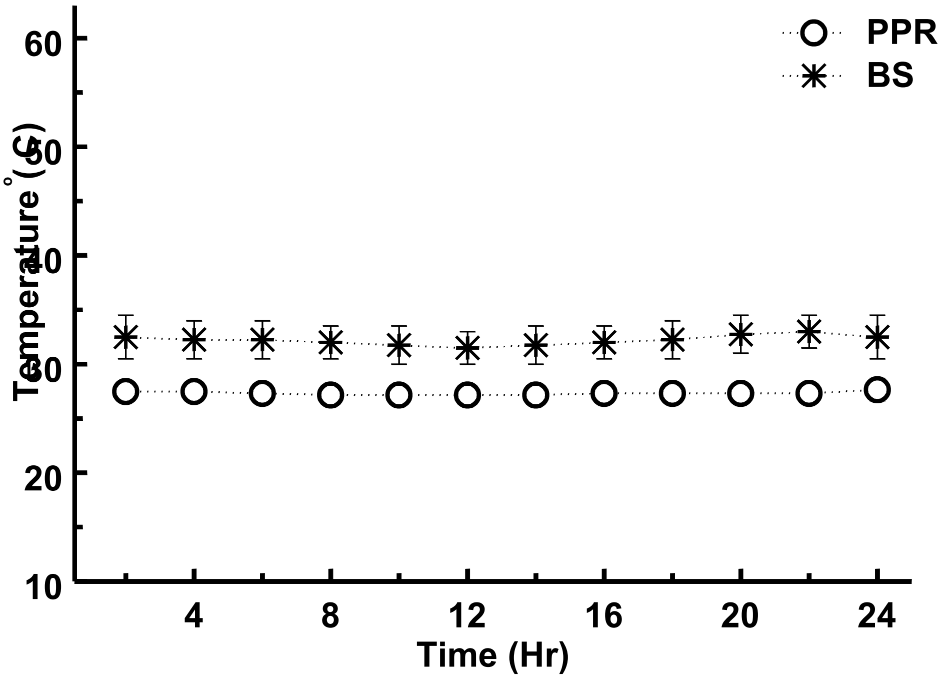

LTT
PPR
DG
BS
Temperature °(C)
60
50
40
30
20
10
4
8
12
16
20
24
Time (Hr)

Figure B.3. Effect of landscape surface mulch treatments on mean diel soil temperatures under *Nerium oleander* shrub canopy at a 30-cm depth during: A) May, B) August and C) November 2004. Landscape surface mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG) and bare soil (BS). Values are treatment means (LTT, PPR, DG n = 4 and BS n = 2); vertical lines represent ± SE of the means; where not visible ± SE is smaller than symbol size.

A


LTT
PPR
DG
BS
Temperature °C
60
50
40
30
20
10
4
8
12
16
20
24
Time (Hr)

B


PPR
BS
Temperature °C
60
50
40
30
20
10
4
8
12
16
20
24
Time (Hr)

C

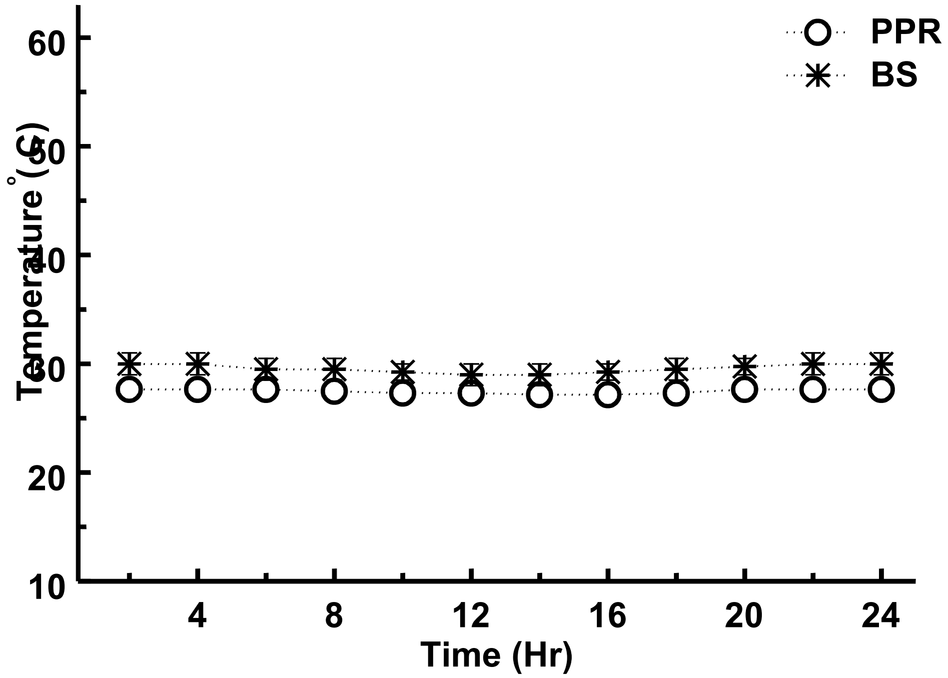
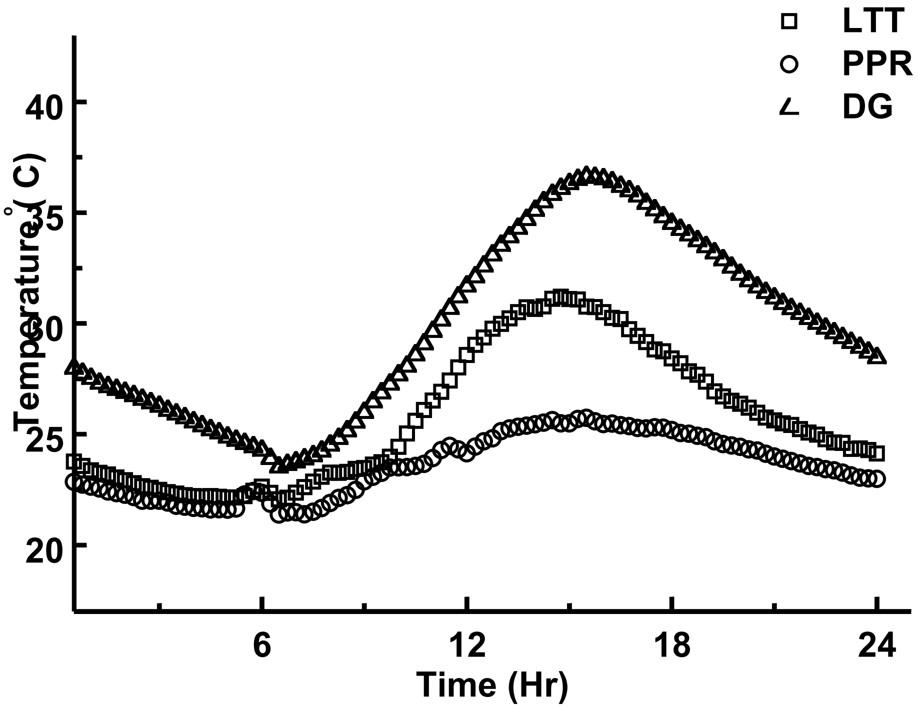
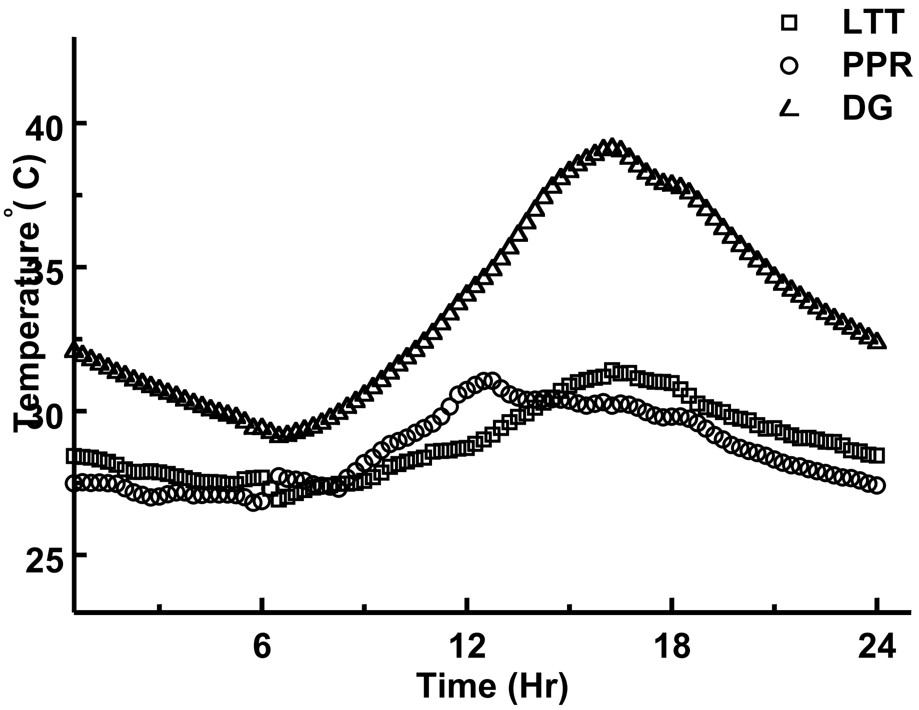


Figure B.4. Effect of landscape surface mulch treatments on mean diel soil temperatures under *Nerium oleander* shrub canopy at a 30-cm depth during: A) April, B) July and C) October 2005. Landscape surface mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG) and bare soil (BS). Values are treatment means (LTT, PPR, DG n = 4 and BS n = 2); vertical lines represent ± SE of the means; where not visible ± SE is smaller than symbol size.

A


LTT
PPR
DG
Temperature (°C)
40
35
30
25
20
6
12
18
24
Time (Hr)

B


LTT
PPR
DG
Temperature (°C)
40
35
30
25
6
12
18
24
Time (Hr)

C

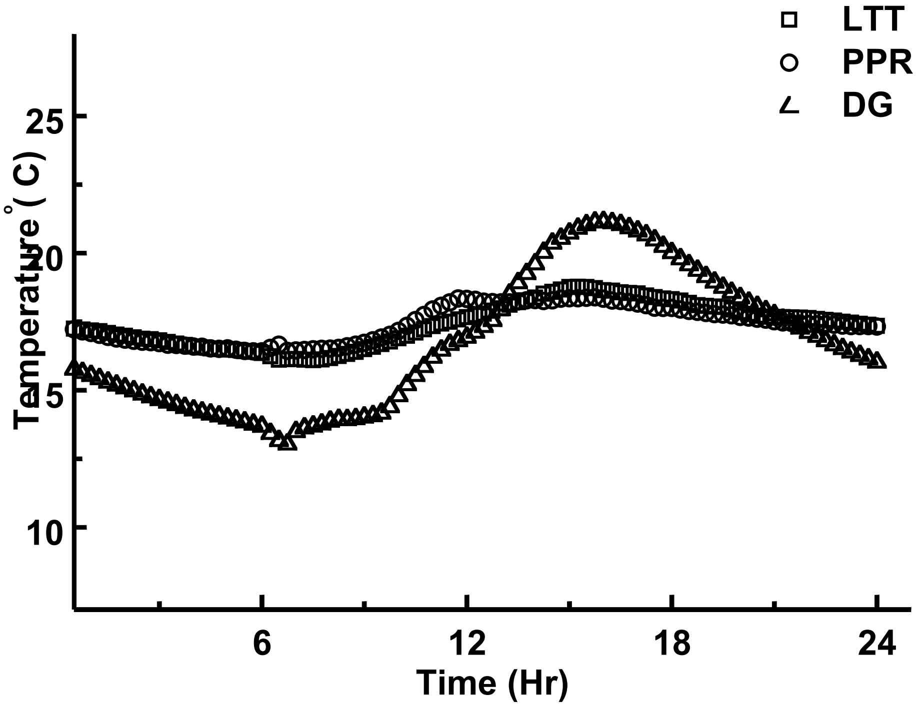
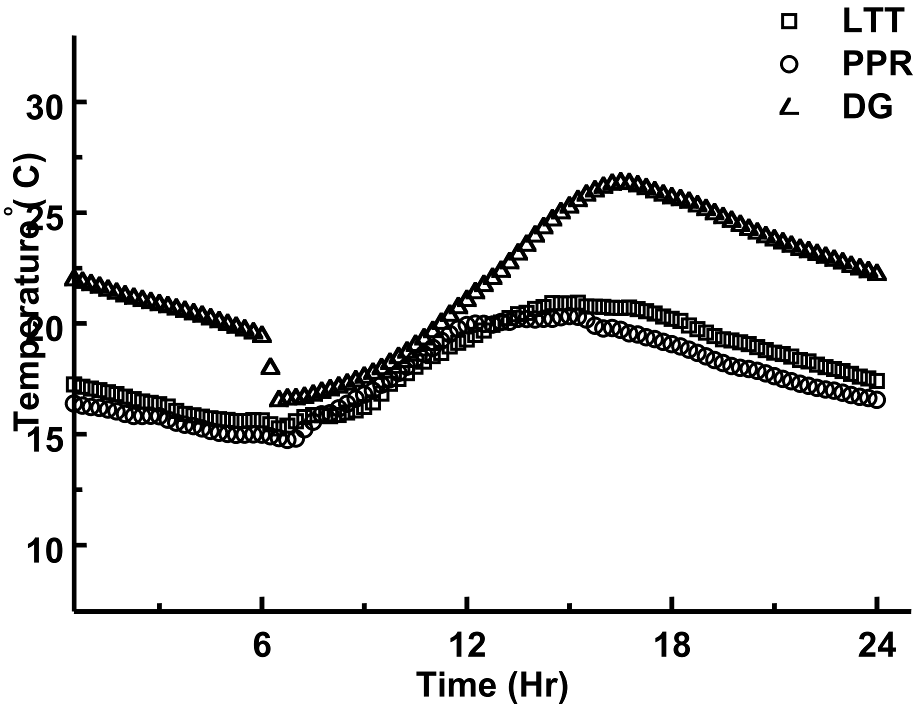


Figure B.5. Effect of landscape surface mulch treatments on mean diel soil surface temperatures under *Nerium oleander* shrub canopy beneath landscape surface mulches during: A) May, B) August and C) November 2004. Landscape surface mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG). Values are treatment means (n = 4).

A


LTT
PPR
DG
Temperature °(C)
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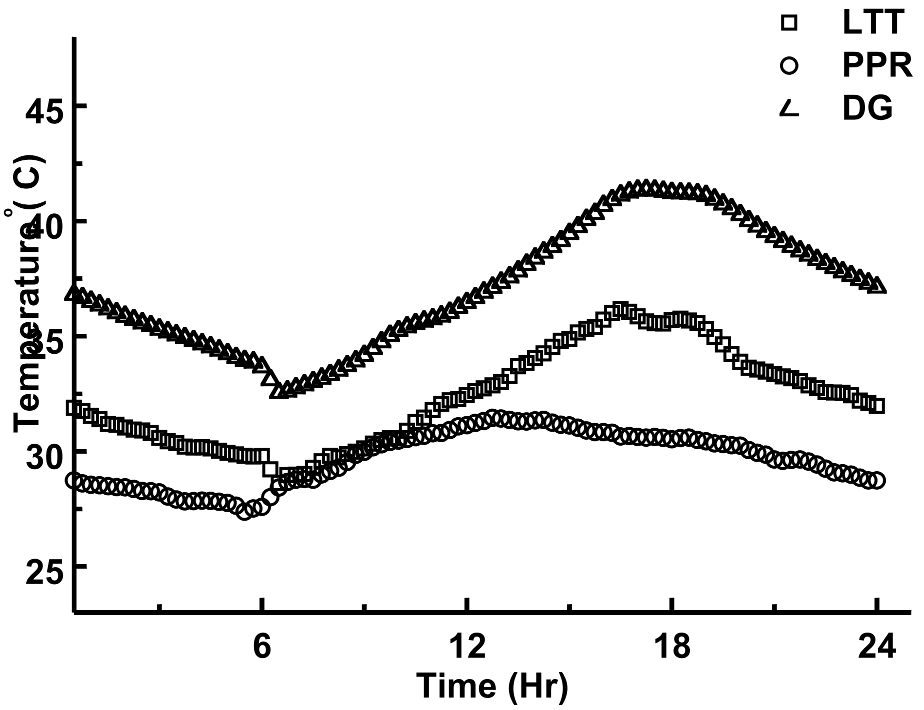
Time (Hr)

B


LTT
PPR
DG
Temperature °(C)
45
40
35
30
25
6
12
18
24
Time (Hr)

C

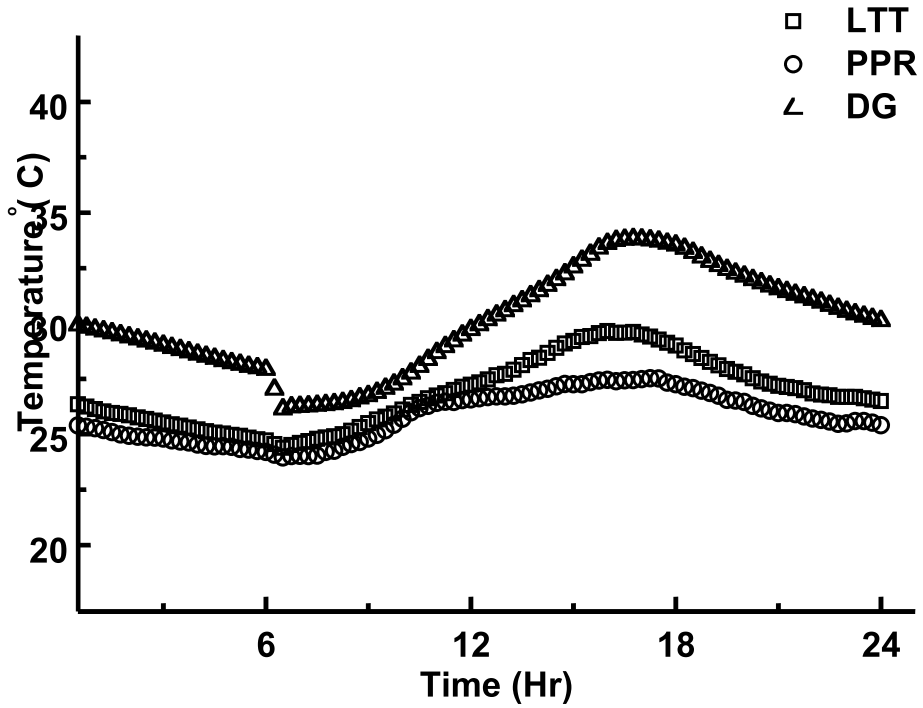
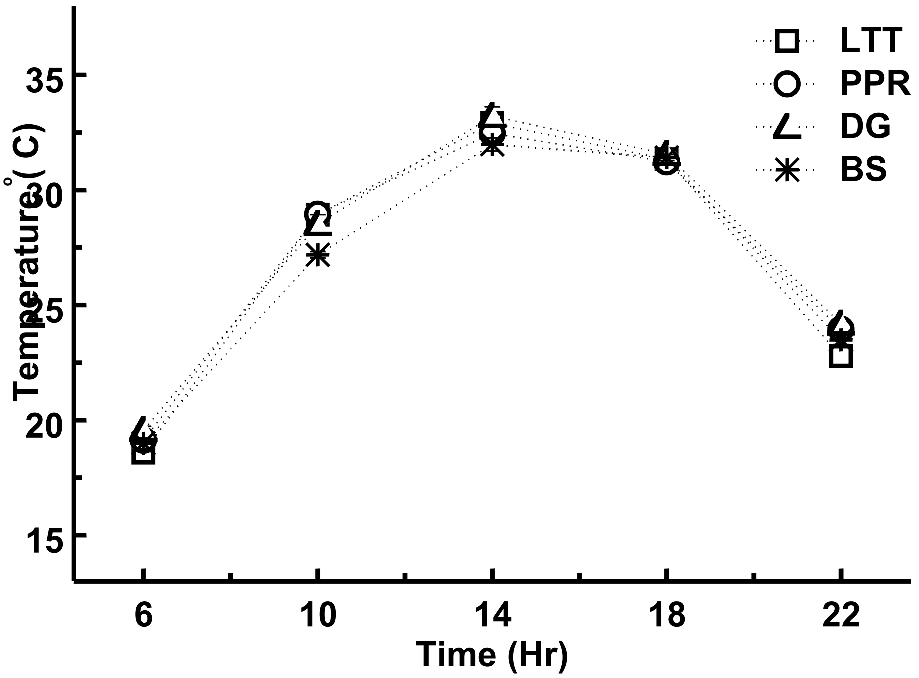
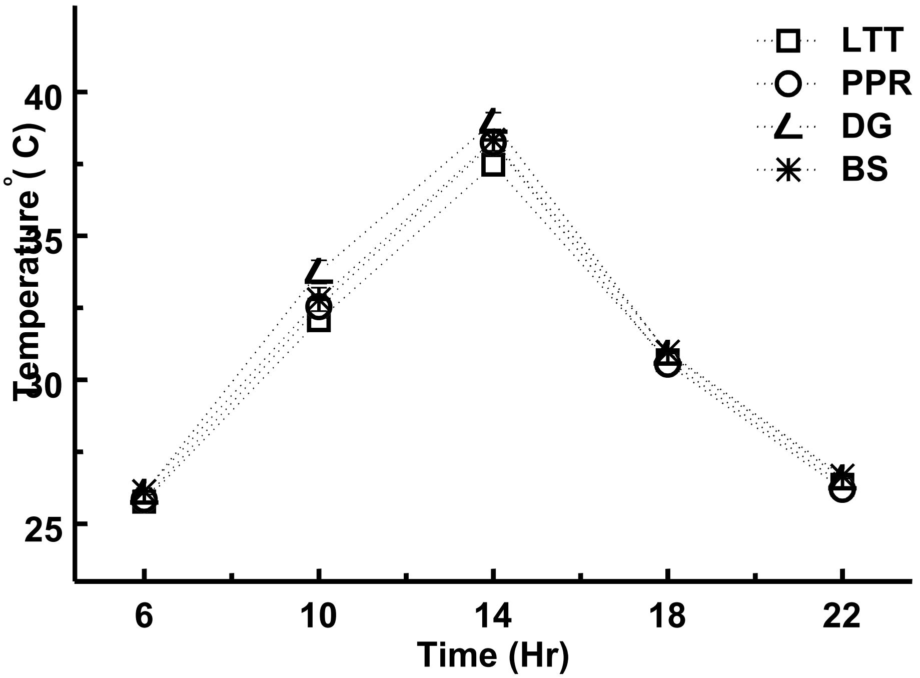


Figure B.6. Effect of landscape surface mulch treatments on mean diel soil surface temperatures under *Nerium oleander* shrub canopy beneath landscape surface mulches during: A) April, B) July and C) October 2005. Landscape surface mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG). Values are treatment means (n = 4).

A


LTT
PPR
DG
BS
Temperature °(C)
35
30
25
20
15
6
10
14
18
22
Time (Hr)

B


LTT
PPR
DG
BS
Temperature °(C)
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18
22
Time (Hr)

C

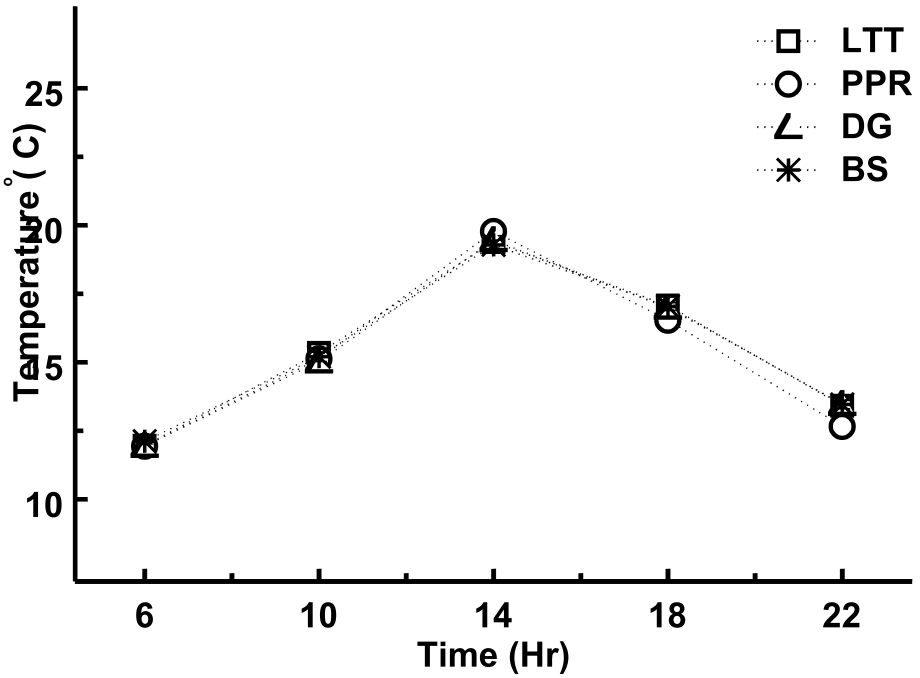
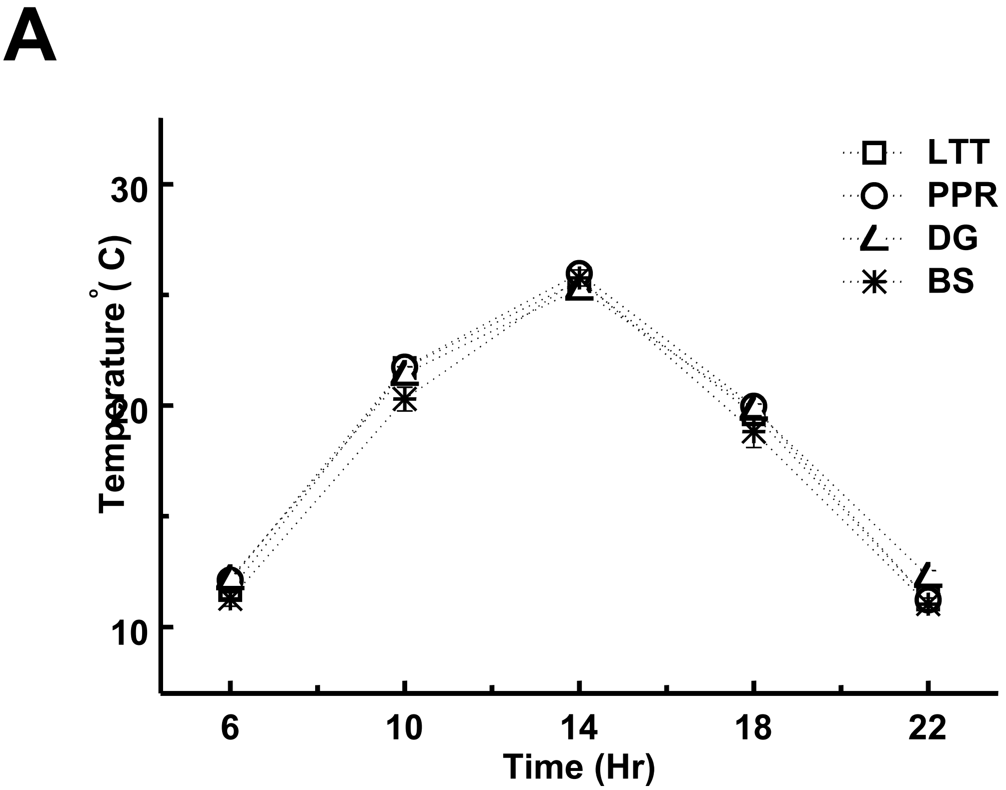


Figure B.7. Effect of landscape surface mulches on mean diel *Nerium oleander* shrub canopy temperature during: A) May, B) August and C) November 2004. Landscape surface mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG) and bare soil (BS). Values are treatment means (LTT, PPR, DG n = 24 and BS n = 12); vertical lines represent ± SE of the means; where not visible ± SE is smaller than symbol size.


A
Temperature °(C)
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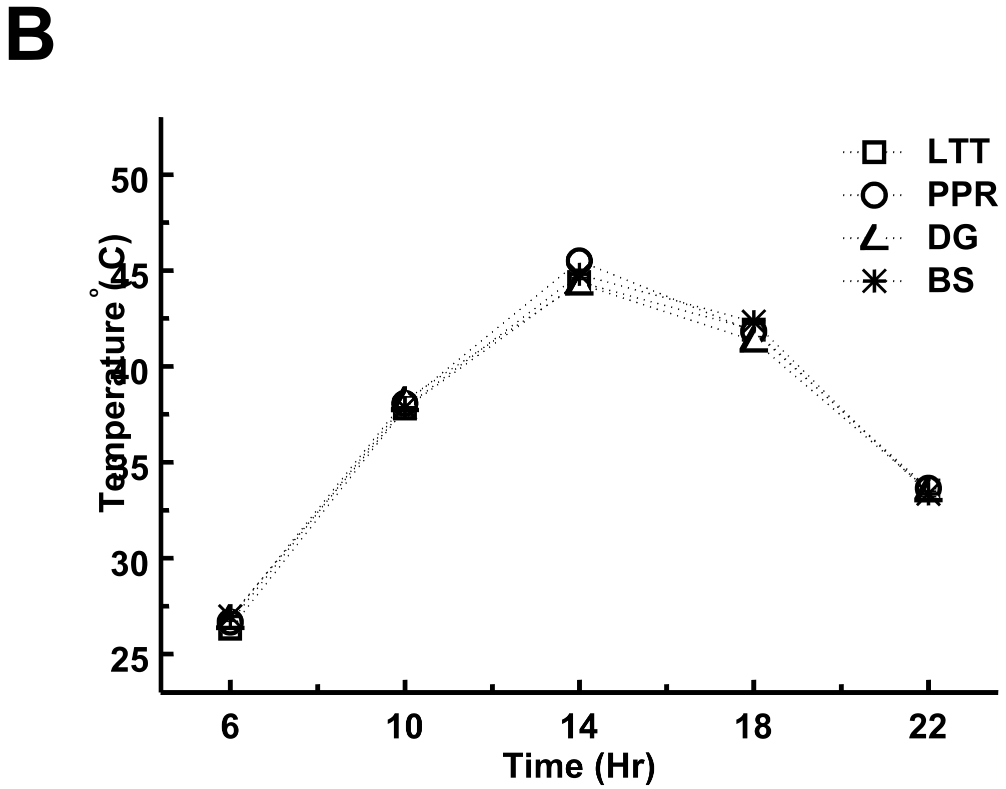
10
6
10
14
18
22
Time (Hr)
LTT
PPR
DG
BS


B
Temperature °(C)
50
45
40
35
30
25
6
10
14
18
22
Time (Hr)
LTT
PPR
DG
BS

C

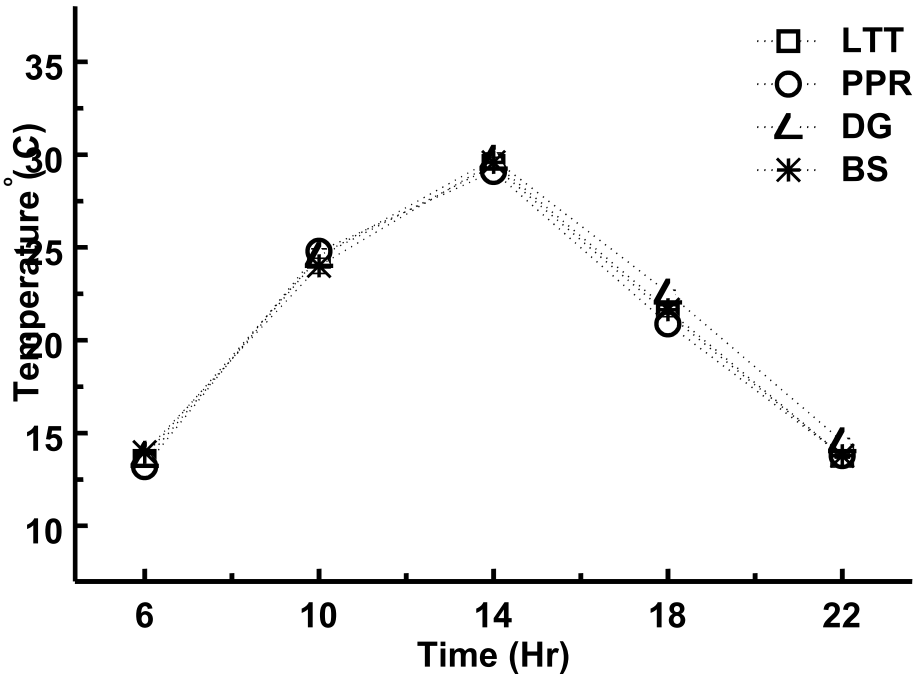
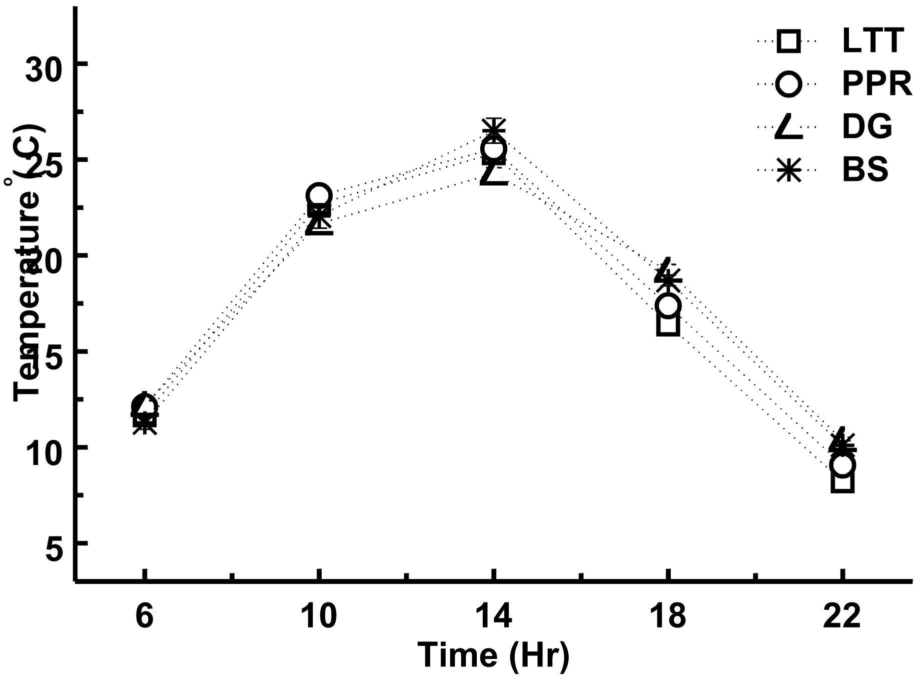


Figure B.8. Effect of landscape surface mulches on mean diel *Nerium oleander* shrub canopy temperature during: A) April, B) July and C) October 2005. Landscape surface mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG) and bare soil (BS). Values are treatment means (LTT, PPR, DG n = 24 and BS n = 12); vertical lines represent ± SE of the means; where not visible ± SE is smaller than symbol size.

A


LTT
PPR
DG
BS
Temperature °(C)
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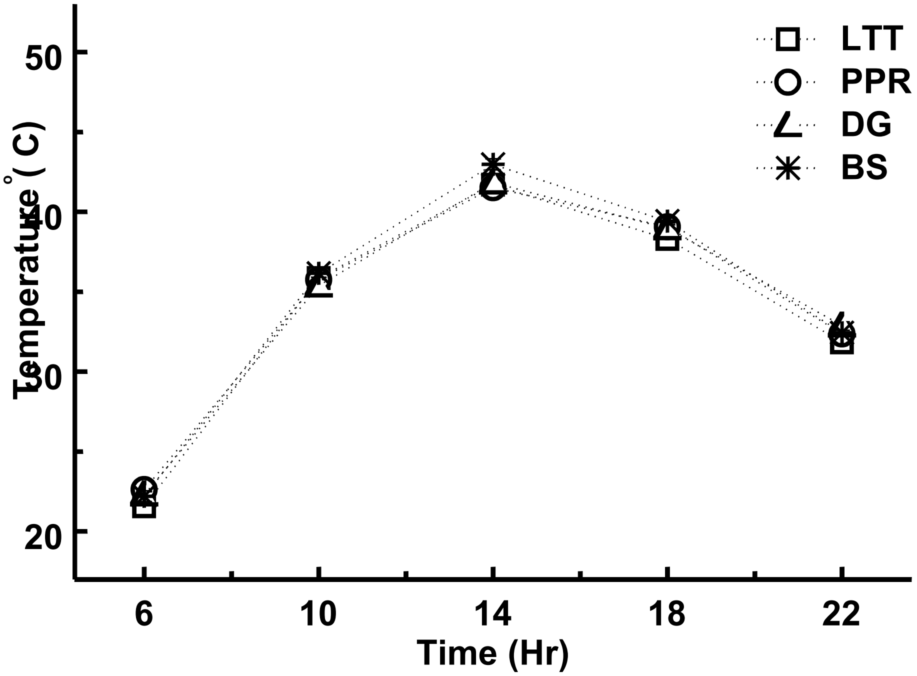
Time (Hr)

B


LTT
PPR
DG
BS
Temperature °(C)
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40
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20
6
10
14
18
22
Time (Hr)

C

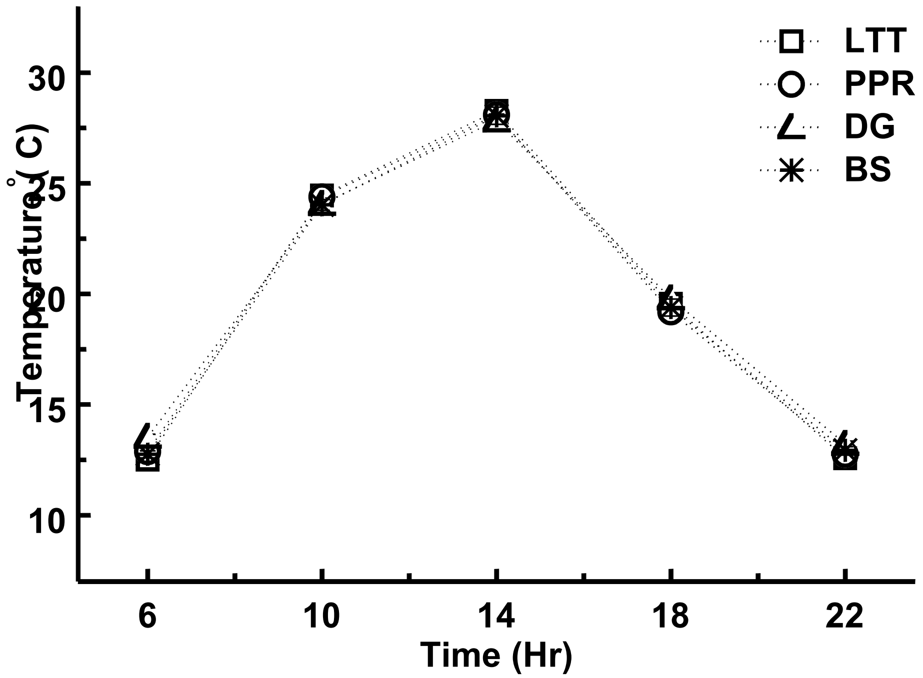

Figure B.9. Effect of landscape surface mulches on mean diel *Leucophyllum frutescens* shrub canopy temperature during: A) April, B) July and C) October 2005. Landscape surface mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG) and bare soil (BS). Values are treatment means (LTT, PPR, DG n = 24 and BS n = 12); vertical lines represent ± SE of the means; where not visible ± SE is smaller than symbol size.

Table B.1. Spring, summer and fall soil respiration (Rs) fluxes by mulch type and location (open un-shaded location and under drip-irrigated *Nerium oleander* canopy) during 2004. Treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG) and bare soil (BS).

		Rs (μmol/m^2/s)		
Mulch	Location	May	Aug	Nov
LTT	open	-0.33^z ab^y	-0.54 a	-4.41 c
LTT	canopy	-1.71 c	-1.64 b	-3.14 bc
PPR	open	-0.44 ab	-0.51 a	-1.29 a
PPR	canopy	-1.00 b	-1.44 b	-1.64 ab
DG	open	-0.61 ab	-0.55 a	-0.76 a
DG	canopy	-1.10 bc	-1.36 b	-1.30 a
BS	open	-0.20 ab	-0.28 a	-1.12 ab
BS	canopy	-1.05 bc	-2.06 b	-2.56 abc

[z] Values are treatment means; LTT, PPR, DG n = 4; BS n = 2.

[y] Mean values within the same column followed by the same letter were not significantly different, using Tukey's HSD test (α = 0.05).

Table B.2. Spring, summer and fall soil respiration (Rs) fluxes by mulch type and location (open un-shaded location and under drip-irrigated *Nerium oleander* canopy) during 2005. Treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG) and bare soil (BS).

		Rs (μmol/m^2/s)		
Mulch	Location	Apr	Jul	Nov
LTT	open	-1.10^z a^y	-0.90 a	-0.54 a
LTT	canopy	-1.60 ab	-3.36 c	-2.17 c
PPR	open	-0.94 a	-0.87 a	-0.69 ab
PPR	canopy	-1.19 a	-3.37 c	-1.47 bc
DG	open	-1.05 a	-1.06 ab	-0.56 a
DG	canopy	-2.64 b	-2.64 bc	-1.58 bc
BS	open	-0.74 a	-0.83 a	-0.61 ab
BS	canopy	-2.26 ab	-2.51 abc	-1.28 abc

[z] Values are treatment means, LTT, PPR, DG n = 4; BS n = 2.

[y] Mean values within the same column followed by the same letter were not significantly different, using Tukey's HSD test (α = 0.05).

Table B.3. Mean leaf chlorophyll content (mg/g) of *Nerium oleander* shrubs growing in landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG) and bare soil (BS) during 2004 and 2005.

	Leaf chlorophyll content (mg/g)					
	2004			2005		
Treatment	Apr	Jul	Oct	Apr	Jul	Oct
LTT	3.20[z]a[y]	3.30 a	3.23 a	3.16 ab	3.36 a	3.20 a
PPR	3.11 b	3.28 a	3.21 a	3.08 b	3.36 a	3.21 a
DG	3.14 ab	3.32 a	3.22 a	3.11 a	3.36 a	3.25 a
BS	3.15 ab	3.33 a	3.16 a	3.19 b	3.37 a	3.22 a

[z] Values are treatment means, LTT, PPR, DG n = 24, BS n = 12.

[y] Mean values within the same column followed by the same letter were not significantly different, using Tukey's HSD test ($\alpha = 0.05$).

Table B.4. Effect of landscape surface mulch on mean percent leaf relative water content (RWC) of *Nerium oleander* during April, July and October 2004. Landscape mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR) and decomposing granite (DG).

	Nerium leaf RWC (%)		
Mulch	Apr	Jul	Oct
LTT	86.5[z] ab[y]	81.6 ab	88.1 a
PPR	87.7 a	83.9 a	88.3 a
DG	85.8 b	79.8 b	87.6 a

[z] Values are treatment means, n = 24.

[y] Mean values within the same column followed by the same letter were not significantly different for irrigation treatment by mulch treatment using Student's t-test ($\alpha = 0.05$).

Table B.5. Effect of landscape surface mulch on mean percent leaf relative water content (RWC) of *Nerium oleander* during April, August and October 2005. Landscape mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR) and decomposing granite (DG).

	Nerium leaf RWC (%)		
Mulch	Apr	Aug	Oct
LTT	89.9[z] a[y]	80.0 a	88.4 a
PPR	89.4 a	79.1 a	86.1 a
DG	89.6 a	79.9 a	85.9 a

[z] Values are treatment means, n = 24.

[y] Mean values within the same column followed by the same letter were not significantly different for irrigation treatment by mulch treatment using Student's t-test ($\alpha = 0.05$).

Table B.6. Effect of landscape surface mulches on mean final harvest growth index [$(h + w_1 + w_2)/3$] and total shoot fresh mass of *Nerium oleander* shrubs (2004 and 2005). Landscape surface mulches were landscape tree trimmings (LTT), ponderosa pine residue (PPR) and decomposing granite (DG).

Mulch	Growth index (m)		Shoot mass (kg)	
	2004	2005	2004	2005
LTT	1.00[z] a[y]	1.15 a	2.82 a	3.83 a
PPR	0.95 a	0.97 b	2.38 a	2.42 a
DG	0.94 a	1.08 ab	2.64 a	3.42 a

[z] Values are treatment means, n = 24.

[y] Mean values within the same column followed by the same letter were not significantly different, using Tukey's HSD test ($\alpha = 0.05$).

Table B.7. Effect of landscape surface mulches on specific leaf mass (SLM) of *Nerium oleander* and *Leucophyllum frutescens* shrubs during fall 2004 and 2005. Landscape surface mulches were landscape tree trimmings (LTT), ponderosa pine residue (PPR) and decomposing granite (DG).

Mulch	*Nerium* SLM		*Leucophyllum* SLM	
	2004	2005	2004	2005
LTT	0.0190[z] a[y]	0.0188 a	0.0087 a	0.0091 a
PPR	0.0186 a	0.0188 a	0.0087 a	0.0097 a
DG	0.0190 a	0.0189 a	0.0091 a	0.0093 a

[z] Values are treatment means, n = 24.

[y] Mean values within the same column followed by the same letter were not significantly different, using Tukey’s HSD test ($\alpha = 0.05$).

Table B.8. Effect of landscape surface mulches on mean final harvest growth index [$(h + w_1 + w_2)/3$] and total shoot fresh mass of *Leucophyllum frutescens* shrubs (2004 and 2005). Landscape surface mulches were landscape tree trimmings (LTT), ponderosa pine residue (PPR) and decomposing granite (DG).

Mulch	Growth index (m)		Shoot mass (kg)	
	2004	2005	2004	2005
LTT	0.80[z] a[y]	0.97 a	1.16 a	1.47 a
PPR	0.84 a	0.85 b	1.25 a	1.10 a
DG	0.75 a	0.88 ab	1.14 a	1.29 a

[z] Values are treatment means, n = 24.

[y] Mean values within the same column followed by the same letter were not significantly different, using Tukey's HSD test ($\alpha = 0.05$).

Table B.9. Mean leaf chlorophyll content (mg/g) of *Leucophyllum frutescens* shrubs growing in landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG) and bare soil (BS) during 2004 and 2005.

	Leaf chlorophyll content (mg/g)					
	2004			2005		
Treatment	Apr	Jul	Oct	Apr	Jul	Oct
LTT	3.73[z] ab[y]	4.03 a	5.21 a	4.15 a	3.70 a	5.07 a
PPR	3.52 b	3.63 b	4.96 ab	3.97 ab	3.54 a	4.73 b
DG	3.92 a	3.79 ab	4.81 b	3.69 b	3.64 a	4.68 b
BS	3.45 b	3.88 ab	4.99 ab	3.88 ab	3.56 a	4.97 ab

[z] Values are treatment means, LTT, PPR, DG n = 24, BS n = 12.

[y] Mean values within the same column followed by the same letter were not significantly different, using Tukey's HSD test ($\alpha = 0.05$).

Table B.10. Mean percent nodes with leaves on *Leucophyllum frutescens* shoots grown in landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG), and bare soil (BS) during October 2004.

	Nodes with leaves (%)
LTT	66.5 b
PPR	70.4 b
DG	82.9 a
BS	73.5 ab

[z] Values are treatment means; LTT, PPR, DG n = 24; BS n = 12.

[y] Mean values within the same column followed by the same letter were not significantly different, using Tukey's HSD test ($\alpha = 0.05$).

Table B.11. Mean number of weeds per landscape surface mulch during February 2005. Landscape surface mulch treatments were landscape tree trimmings (LTT), ponderosa pine residue (PPR), decomposing granite (DG), and bare soil (BS).

	2005
LTT	5[z] b[y]
PPR	0 b
DG	1060 a
BS	600 ab

[z] Values are treatment means; LTT, PPR, DG n = 4; BS n = 2.

[y] Mean values within the same column followed by the same letter were not significantly different, using Tukey’s HSD test (α = 0.05).