Effect of Residential Landscape Design on Undercanopy Microclimate

by

Kendra D. Busse

A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

ARIZONA STATE UNIVERSITY

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Graduate Supervisory Committee:

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John H. Brock

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ABSTRACT

Understanding environmental factors that influence microclimate at the neighborhood scale is necessary to improve performance of mesoscale urban meteorological models and strategies of urban heat island mitigation. The purpose of this study was to examine the influence of landscape design on microclimates at the neighborhood scale. Four clusters of six residential homes surrounding a public common area were landscaped in 2004 with either one of four archetypical landscape design types (mesic, oasis, xeric, and desert). The mesic, oasis, and xeric treatment areas were normally irrigated with systems that scheduled watering frequencies and durations based on daily evapotranspiration potential demand. The desert treatment was not irrigated. A mobile micrometeorological station was constructed to measure temperatures at heights of 0 m, 0.25 m, 0.5 m 1.0 m, 2.0 m, and 5.0 m, percent relative humidity, and saturation vapor pressure at 2.0 m. Morning, afternoon, and evening micrometeorological data were recorded during pre-monsoon, monsoon and winter conditions of 2007-08. Overall, temperatures in the mesic and oasis treatment areas were cooler than in the xeric and desert treatment areas to approximately 2 m above the surface during pre-monsoon conditions and 1 m above the surface during monsoon conditions. Percent relative humidity and saturation vapor pressure were generally not affected by design treatment. These findings clearly demonstrate the important role of landscape surface cover type to mitigate urban heating by modifying the surface energy balance, especially

during the years after landscape installation but before tree canopies are established to provide maximum shade potential.

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There are many factors that influence the UHI, such as building type, building density, use of plant material, and choice of surface cover. Many of these factors are determined by how the land is used; including tightly packed high-rise buildings, industrial and commercial properties, transportation, undeveloped or maintained open space, natural features, landfills, agriculture, and residential areas (Stabler et al., 2005). This study will focus on variations in the structural composition of vegetation of residential neighborhoods of the Phoenix metropolitan area.

In Maricopa County, which contains Phoenix, residential property is the single largest use of developed land, except for agriculture. The residential land-use classification contains more than ten times the number of acres than either commercial or industrial classifications, and previous research has shown that residential land use comprises about 70% of the total land use in the Phoenix metropolitan region (Maricopa Association of Governments, 2004; Stabler, 2003). Sub-classifications break down residential land-use into categories based on number of dwelling units per acre. This classification system does not, however, reflect the variation of landscape designs used in the Phoenix valley.

Because of the overwhelming proportion of land-use dedicated to residential areas, understanding how the environmental factors which influence the UHI are played out in a residential setting is necessary in order to develop ways of mitigating the UHI. However, studying and understanding the UHI in a residential setting proves to be challenging. In contrast to other landscapes, such as municipal street-scapes, public areas or business landscapes, which have more homogeneity within their landscapes, individual homeowners have more control, more options and potentially more involvement in shaping their residential landscapes. Phoenix residential neighborhood landscapes vary in composition from a desert-like landscape with little irrigation to landscapes with varying amounts of turf-grass and low-water use plants to landscapes with extensive turf-grass and large shade trees (Hope et al., 2003; Martin and Stabler, 2004).

Most UHI studies focus on the comparison between urban and rural temperatures, but do little to distinguish among variations within the urban setting, and even less between residential landscape design types. As a result, a major portion of land-use within the urban setting has been understudied. Additionally, most UHI studies obtain data on a large scale. Temperatures are collected largely by using remote sensing for surface temperatures, city-wide meteorological stations, or cross-urban transects (Avissar, 1996; Hedquist and Brazel, 2006; Caparrini et al., 2003; Unger, et al. 2001; Fast et al., 2005; Yuan and Bauer, 2007; Jenerette et al., 2007). One exception is a study by Hartz et al. (2006), which combined several methods of temperature collection to compare surface and air (1.5 m) temperatures in three different Phoenix neighborhoods. In contrast to the present study, however, Hartz et al. (2006) focused primarily on housing density and not landscape design style. As a result, it is unclear how the wide variety of landscape design styles that are implemented in Phoenix residential areas factor into the larger UHI issue.

The wide variety of landscape design styles present in Phoenix are the result of shifting popular attitudes regarding landscape function and resource use. Residential areas built before air conditioning became commonly available in the 1950's featured landscapes comprised extensively of large shade trees, broad leaf shrubbery and flood irrigated lawns. The concentration of water and vegetation in these landscapes utilized high rates of evapotranspirational cooling to mitigate the hot summer conditions (Sailor, 1998). With the increasing

availability of residential air conditioning, public emphasis has shifted away from a landscapes' ability to provide cooling towards reducing water consumption and the preservation of the Sonoran Desert (Larson, et al., 2009; Hurd, 2006; St. Hilaire et al., 2008, Sovocool et al., 2006).

Phoenix's rapid population growth in the last 50 years and concerns regarding water resources has led to a popular effort to find low-water use plants. Landscape vegetation in the Phoenix metropolitan region is normally irrigated because on average the climate of the Sonoran Desert shows an 1843 mm per year evaporation potential deficit (The Arizona Meteorological Network, 2010). It is clear that design styles which feature drought-tolerant plants use less irrigation than the turf grass dominated design styles that had been previously utilized. However, it is unclear how changes in landscape design styles affect other ecological processes and potential benefits derived from more traditional landscapes.

Ecologist have recently started trying to assign a monetary value to the benefits provided by ecological systems, for example, heat mitigation, recreation, air quality restoration, runoff control, wildlife habitat and dust control (Plummer, 2009, Harlan et al., 2006; Akbari et al., 2001, Baker et al., 2002; Pickett et al., 2001, Costanza et al., 1997). However, the environmental and economic benefits provided by urban ecosystems in the southwest have received little attention, despite the fact that the southwest has recently seen some of the highest population growth in the United States. A better understanding of the benefits

and costs of various landscape design styles will help in determining ecologically sustainable landscape designs (Shen et al., 2008; Grimm et al., 2008; Wu, 2007; Golden 2004). One important component of landscape design style is surface cover, because surface cover greatly impacts the amount of heat that enters the soil (Singer and Martin, 2008; Mueller and Day, 2005; Chalker-Scott, 2007). The two major landscape cover types used in Phoenix are turf grass and decomposed granite mulch.

This study seeks to examine the influence of landscape cover type on the surrounding environment at the neighborhood scale. It differs from other studies in two significant ways. First, emphasis is given to landscape design styles as the major difference among treatments. The difference in design styles was reflected mainly in the implantation surface cover, tree and shrub taxa, and irrigation regimes. Secondly, this study examined microclimate variables starting at the surface and extending through the undercanopy profile to a height of 5 m at a fine scale resolution. An analysis of the differences in surface and air temperatures at the neighborhood scale will lead to a better understanding of how landscape choices affect mesoscale climate patterns. This research tested the hypothesis that the mesic and oasis treatments would exhibit distinctly cooler surface and air temperatures among the four tested treatments design styles within 5.0 m above the surface. Additionally, this study tested the hypothesis that observed microclimate effects within the treatments would be more pronounced during premonsoon conditions than during monsoon conditions.

Chapter 2

Material And Methods

The purpose of this research study was to characterize the effect of surface cover as part of landscape design on the microclimate conditions at the neighborhood scale in a Phoenix area residential setting. Four treatment sites, representing four archetypes of landscape design found in the Phoenix metropolitan area, were used to measure surface and air temperatures throughout the day during summer 2007 and winter 2008.

Phoenix weather patterns are dominated by early summer (May through early July) high-pressure systems which lead to hot dry weather, and late summer (mid July through September) monsoon. The thirty-year average high temperature during the month of June is 39.2°C. The thirty-year average high during August, in the middle of the monsoon period, is 40.6°C. The thirty- year average high for February is 21.8°C. (PRISM Climate Group, 2010).

Overall climate conditions of summer 2007 and winter 2008 were typical for the Phoenix valley. The average maximum temperature in June was 39.6° C , which is +0.4°C above the thirty-year average. The average maximum temperature in August was 40.9°C, a difference of +0.3°C from the 30-year average. The average maximum temperature in February was 19.7°C, which is -2.1°C below the thirty-year average (PRISM Climate Group, 2010).

The Phoenix metropolitan area is located in large, wide valley in southern Arizona. It is comprised of several cities, which form a semi-contiguous sprawl of

intermixed urban, residential and industrial areas surrounded by Sonoran desert and irrigated agricultural areas. As the population continues to expand at an increasing rate, urban development encroaches and replaces agricultural fields and virgin desert.

The treatment sites were in an area of student housing located at The Arizona State University Polytechnic campus, which was, until 1997, Williams Air Force Base. Each treatment consisted of six single-story houses, and their associated yards, arranged around a central common area. The houses were constructed during the 1950's and are mostly three bedroom homes with similar floor plans. They were of cement block construction, covered in stucco and painted in earth tones. The common area was separated from the back yards of each house by a concrete path. An asphalt road circumscribed approximately three quarters of the borders of each treatment. Table 1 shows the amount of area covered by homes, hardscape, decomposing granite mulch, turf grass and bare soil in each treatment.

The four treatment sites were landscaped during Spring 2005 as part of the Central Arizona Phoenix Long Term Ecological Research project (CAP LTER). CAP LTER is funded by the National Science Foundation to study urban ecological issues and processes. These four treatment sites were established to provide a controlled residential setting for ecological research at the neighborhood scale. They were planted to reflect archetypes of the four most common landscape design styles found in the Phoenix metropolitan area. Each

Table 1.

Land cover distribution (m^2) of the four residential landscape design treatment areas.

Land cover type	Treatment Mesic	Oasis	Xeric	Desert
Homes	1278	1164	1237	1223
Impervious cover Asphalt concrete walks & carports	547	477	416	422
Pervious cover Decomposing granite	0	3703	4788	4648
Turf grass	3951	442	0	0
Bare soil	0	0	0	0
Total	5776	5786	6441	6293

treatment had plant selection, primary ground cover and irrigation methods similar to local residential landscapes. They were mesic (high water use), oasis (mixed water use), xeric (low water use), and desert (non-irrigated).

The mesic treatment (Fig. 1) was dominated by sprinkler irrigated turf grass, which covered all unpaved areas. Several large extant bottle trees [*Brachychiton populneus* (Schott & Endl.) R. Br.] were left when the treatment was established. A complete list of tree and shrub species can be found on Table 2. Several of the shrub specimens that were planted in the mesic treatment area in 2005 were destroyed by local landscape maintenance personnel who were charged with mowing the turf grass on a weekly basis.

The oasis treatment (Fig. 1) had a drip-irrigated mixture of high and low water use trees and shrubs, and several patches of sprinkler-irrigated turf. One large rectangular turf patch was located in the middle of the common area. Additionally, small patches of turf grass were conjoined to the back-side of each house in the treatment area. A complete list of tree and shrub species can be found on Table 2.

The xeric treatment (Fig. 1) had drip-irrigated low water use trees and shrubs several of which were hybridized varieties of native plants. A complete list of tree and shrub species can be found on Table 2.

The desert treatment (Fig. 1) contained trees, shrubs and cactus species native to the Sonoran desert. Vegetation in the desert treatment were irrigated by garden hose during the first summer after transplanting to facilitate establishment. A

complete list of tree and shrub species can be found on Table 2. All unpaved and non-turf ground surfaces in the oasis, xeric and desert treatment areas were covered in two inches of decomposing granite mulch. The decomposing granite pieces are beige and approximately 9.5 mm in diameter. The albedo of the decomposing granite mulch was 0.16 ± 0.01 (Singer and Martin, 2008).

Regular landscape maintenance, which consisted mainly of mowing and weed control, was provided to all treatments by a commercial landscape maintenance company. Supplemental irrigation provided to the mesic, oasis and xeric treatment areas were scheduled by a Toro Intelli-Sense™ Series controller (The Toro Company, 2010), which regulated watering schedules based on preprogrammed factors including daily evapotranspirational water loss (ET_o), plant type, soil type, and water delivery rate. These controllers received information regarding local evapotranspiration rates via microwave signals from a service provider (Hydro-Point Data Systems, Inc., 2010) and reprogrammed irrigation schedules daily based on ET_o from the previous day.

A mobile meteorological station was constructed to record temperature, percent relative humidity, and saturation vapor pressure conditions throughout the treatments, (Fig. 2). Shielded constantan-copper thermocouples for recording air temperatures were mounted on a pole at heights of 0.25 m, 0.5 m, 1.0 m and 5.0 m. A shielded HMP45C-L probe (Campbell Scientific, Logan UT) was mounted on the same pole at 2.0 m to record air temperature, percent

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The urban heat island is a well-documented phenomenon that results in temperatures within a city being higher than in the surrounding rural environment (Oke, 1987; Rizwan et al., 2008; Brazel et al., 2007; Jauregui, 1997; Arnfield, 2003). It is mainly caused by the combination of long wave irradiance from building materials that absorb heat, lack of landscape evapotranspirational cooling, and increased heat exhaust from air conditioners, cars and industry (Oke, 1997). In Phoenix, the urban heat island (UHI) is a night-time phenomena (Brazel et al., 2000). During the day, the irrigated landscapes of the city cool the area more than the un-irrigated desert (Souch and Grimmond, 2006). However, at night, the captured heat of the built environment keeps the urban core much warmer than the surrounding Sonoran Desert.

There are many factors that influence the UHI, such as building type, building density, use of plant material, and choice of surface cover. Many of these factors are determined by how the land is used; including tightly packed high-rise buildings, industrial and commercial properties, transportation, undeveloped or maintained open space, natural features, landfills, agriculture, and residential areas (Stabler et al., 2005). This study will focus on variations in the structural composition of vegetation of residential neighborhoods of the Phoenix metropolitan area.

In Maricopa County, which contains Phoenix, residential property is the single largest use of developed land, except for agriculture. The residential land-use classification contains more than ten times the number of acres than either commercial or industrial classifications, and previous research has shown that residential land use comprises about 70% of the total land use in the Phoenix metropolitan region (Maricopa Association of Governments, 2004; Stabler, 2003). Sub-classifications break down residential land-use into categories based on number of dwelling units per acre. This classification system does not, however, reflect the variation of landscape designs used in the Phoenix valley.

Because of the overwhelming proportion of land-use dedicated to residential areas, understanding how the environmental factors which influence the UHI are played out in a residential setting is necessary in order to develop ways of mitigating the UHI. However, studying and understanding the UHI in a residential setting proves to be challenging. In contrast to other landscapes, such as municipal street-scapes, public areas or business landscapes, which have more homogeneity within their landscapes, individual homeowners have more control, more options and potentially more involvement in shaping their residential landscapes. Phoenix residential neighborhood landscapes vary in composition from a desert-like landscape with little irrigation to landscapes with varying amounts of turf-grass and low-water use plants to landscapes with extensive turf-grass and large shade trees (Hope et al., 2003; Martin and Stabler, 2004).

Most UHI studies focus on the comparison between urban and rural temperatures, but do little to distinguish among variations within the urban setting, and even less between residential landscape design types. As a result, a major portion of land-use within the urban setting has been understudied. Additionally, most UHI studies obtain data on a large scale. Temperatures are collected largely by using remote sensing for surface temperatures, city-wide meteorological stations, or cross-urban transects (Avissar, 1996; Hedquist and Brazel, 2006; Caparrini et al., 2003; Unger, et al. 2001; Fast et al., 2005; Yuan and Bauer, 2007; Jenerette et al., 2007). One exception is a study by Hartz et al. (2006), which combined several methods of temperature collection to compare surface and air (1.5 m) temperatures in three different Phoenix neighborhoods. In contrast to the present study, however, Hartz et al. (2006) focused primarily on housing density and not landscape design style. As a result, it is unclear how the wide variety of landscape design styles that are implemented in Phoenix residential areas factor into the larger UHI issue.

The wide variety of landscape design styles present in Phoenix are the result of shifting popular attitudes regarding landscape function and resource use. Residential areas built before air conditioning became commonly available in the 1950's featured landscapes comprised extensively of large shade trees, broad leaf shrubbery and flood irrigated lawns. The concentration of water and vegetation in these landscapes utilized high rates of evapotranspirational cooling to mitigate the hot summer conditions (Sailor, 1998). With the increasing

availability of residential air conditioning, public emphasis has shifted away from a landscapes' ability to provide cooling towards reducing water consumption and the preservation of the Sonoran Desert (Larson, et al., 2009; Hurd, 2006; St. Hilaire et al., 2008, Sovocool et al., 2006).

Phoenix's rapid population growth in the last 50 years and concerns regarding water resources has led to a popular effort to find low-water use plants. Landscape vegetation in the Phoenix metropolitan region is normally irrigated because on average the climate of the Sonoran Desert shows an 1843 mm per year evaporation potential deficit (The Arizona Meteorological Network, 2010). It is clear that design styles which feature drought-tolerant plants use less irrigation than the turf grass dominated design styles that had been previously utilized. However, it is unclear how changes in landscape design styles affect other ecological processes and potential benefits derived from more traditional landscapes.

Ecologist have recently started trying to assign a monetary value to the benefits provided by ecological systems, for example, heat mitigation, recreation, air quality restoration, runoff control, wildlife habitat and dust control (Plummer, 2009, Harlan et al., 2006; Akbari et al., 2001, Baker et al., 2002; Pickett et al., 2001, Costanza et al., 1997). However, the environmental and economic benefits provided by urban ecosystems in the southwest have received little attention, despite the fact that the southwest has recently seen some of the highest population growth in the United States. A better understanding of the benefits

and costs of various landscape design styles will help in determining ecologically sustainable landscape designs (Shen et al., 2008; Grimm et al., 2008; Wu, 2007; Golden 2004). One important component of landscape design style is surface cover, because surface cover greatly impacts the amount of heat that enters the soil (Singer and Martin, 2008; Mueller and Day, 2005; Chalker-Scott, 2007). The two major landscape cover types used in Phoenix are turf grass and decomposed granite mulch.

This study seeks to examine the influence of landscape cover type on the surrounding environment at the neighborhood scale. It differs from other studies in two significant ways. First, emphasis is given to landscape design styles as the major difference among treatments. The difference in design styles was reflected mainly in the implantation surface cover, tree and shrub taxa, and irrigation regimes. Secondly, this study examined microclimate variables starting at the surface and extending through the undercanopy profile to a height of 5 m at a fine scale resolution. An analysis of the differences in surface and air temperatures at the neighborhood scale will lead to a better understanding of how landscape choices affect mesoscale climate patterns. This research tested the hypothesis that the mesic and oasis treatments would exhibit distinctly cooler surface and air temperatures among the four tested treatments design styles within 5.0 m above the surface. Additionally, this study tested the hypothesis that observed microclimate effects within the treatments would be more pronounced during premonsoon conditions than during monsoon conditions.

Chapter 2

Material And Methods

The purpose of this research study was to characterize the effect of surface cover as part of landscape design on the microclimate conditions at the neighborhood scale in a Phoenix area residential setting. Four treatment sites, representing four archetypes of landscape design found in the Phoenix metropolitan area, were used to measure surface and air temperatures throughout the day during summer 2007 and winter 2008.

Phoenix weather patterns are dominated by early summer (May through early July) high-pressure systems which lead to hot dry weather, and late summer (mid July through September) monsoon. The thirty-year average high temperature during the month of June is 39.2°C. The thirty-year average high during August, in the middle of the monsoon period, is 40.6°C. The thirty- year average high for February is 21.8°C. (PRISM Climate Group, 2010).

Overall climate conditions of summer 2007 and winter 2008 were typical for the Phoenix valley. The average maximum temperature in June was 39.6° C , which is +0.4°C above the thirty-year average. The average maximum temperature in August was 40.9°C, a difference of +0.3°C from the 30-year average. The average maximum temperature in February was 19.7°C, which is -2.1°C below the thirty-year average (PRISM Climate Group, 2010).

The Phoenix metropolitan area is located in large, wide valley in southern Arizona. It is comprised of several cities, which form a semi-contiguous sprawl of

intermixed urban, residential and industrial areas surrounded by Sonoran desert and irrigated agricultural areas. As the population continues to expand at an increasing rate, urban development encroaches and replaces agricultural fields and virgin desert.

The treatment sites were in an area of student housing located at The Arizona State University Polytechnic campus, which was, until 1997, Williams Air Force Base. Each treatment consisted of six single-story houses, and their associated yards, arranged around a central common area. The houses were constructed during the 1950's and are mostly three bedroom homes with similar floor plans. They were of cement block construction, covered in stucco and painted in earth tones. The common area was separated from the back yards of each house by a concrete path. An asphalt road circumscribed approximately three quarters of the borders of each treatment. Table 1 shows the amount of area covered by homes, hardscape, decomposing granite mulch, turf grass and bare soil in each treatment.

The four treatment sites were landscaped during Spring 2005 as part of the Central Arizona Phoenix Long Term Ecological Research project (CAP LTER). CAP LTER is funded by the National Science Foundation to study urban ecological issues and processes. These four treatment sites were established to provide a controlled residential setting for ecological research at the neighborhood scale. They were planted to reflect archetypes of the four most common landscape design styles found in the Phoenix metropolitan area. Each

Table 1.

Land cover distribution (m^2) of the four residential landscape design treatment areas.

Land cover type	Treatment Mesic	Oasis	Xeric	Desert
Homes	1278	1164	1237	1223
Impervious cover Asphalt concrete walks & carports	547	477	416	422
Pervious cover Decomposing granite	0	3703	4788	4648
Turf grass	3951	442	0	0
Bare soil	0	0	0	0
Total	5776	5786	6441	6293

treatment had plant selection, primary ground cover and irrigation methods similar to local residential landscapes. They were mesic (high water use), oasis (mixed water use), xeric (low water use), and desert (non-irrigated).

The mesic treatment (Fig. 1) was dominated by sprinkler irrigated turf grass, which covered all unpaved areas. Several large extant bottle trees [*Brachychiton populneus* (Schott & Endl.) R. Br.] were left when the treatment was established. A complete list of tree and shrub species can be found on Table 2. Several of the shrub specimens that were planted in the mesic treatment area in 2005 were destroyed by local landscape maintenance personnel who were charged with mowing the turf grass on a weekly basis.

The oasis treatment (Fig. 1) had a drip-irrigated mixture of high and low water use trees and shrubs, and several patches of sprinkler-irrigated turf. One large rectangular turf patch was located in the middle of the common area. Additionally, small patches of turf grass were conjoined to the back-side of each house in the treatment area. A complete list of tree and shrub species can be found on Table 2.

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The desert treatment (Fig. 1) contained trees, shrubs and cactus species native to the Sonoran desert. Vegetation in the desert treatment were irrigated by garden hose during the first summer after transplanting to facilitate establishment. A

complete list of tree and shrub species can be found on Table 2. All unpaved and non-turf ground surfaces in the oasis, xeric and desert treatment areas were covered in two inches of decomposing granite mulch. The decomposing granite pieces are beige and approximately 9.5 mm in diameter. The albedo of the decomposing granite mulch was 0.16 ± 0.01 (Singer and Martin, 2008).

Regular landscape maintenance, which consisted mainly of mowing and weed control, was provided to all treatments by a commercial landscape maintenance company. Supplemental irrigation provided to the mesic, oasis and xeric treatment areas were scheduled by a Toro Intelli-Sense™ Series controller (The Toro Company, 2010), which regulated watering schedules based on preprogrammed factors including daily evapotranspirational water loss (ET_o), plant type, soil type, and water delivery rate. These controllers received information regarding local evapotranspiration rates via microwave signals from a service provider (Hydro-Point Data Systems, Inc., 2010) and reprogrammed irrigation schedules daily based on ET_o from the previous day.

A mobile meteorological station was constructed to record temperature, percent relative humidity, and saturation vapor pressure conditions throughout the treatments, (Fig. 2). Shielded constantan-copper thermocouples for recording air temperatures were mounted on a pole at heights of 0.25 m, 0.5 m, 1.0 m and 5.0 m. A shielded HMP45C-L probe (Campbell Scientific, Logan UT) was mounted on the same pole at 2.0 m to record air temperature, percent

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ABSTRACT

Understanding environmental factors that influence microclimate at the neighborhood scale is necessary to improve performance of mesoscale urban meteorological models and strategies of urban heat island mitigation. The purpose of this study was to examine the influence of landscape design on microclimates at the neighborhood scale. Four clusters of six residential homes surrounding a public common area were landscaped in 2004 with either one of four archetypical landscape design types (mesic, oasis, xeric, and desert). The mesic, oasis, and xeric treatment areas were normally irrigated with systems that scheduled watering frequencies and durations based on daily evapotranspiration potential demand. The desert treatment was not irrigated. A mobile micrometeorological station was constructed to measure temperatures at heights of 0 m, 0.25 m, 0.5 m 1.0 m, 2.0 m, and 5.0 m, percent relative humidity, and saturation vapor pressure at 2.0 m. Morning, afternoon, and evening micrometeorological data were recorded during pre-monsoon, monsoon and winter conditions of 2007-08. Overall, temperatures in the mesic and oasis treatment areas were cooler than in the xeric and desert treatment areas to approximately 2 m above the surface during pre-monsoon conditions and 1 m above the surface during monsoon conditions. Percent relative humidity and saturation vapor pressure were generally not affected by design treatment. These findings clearly demonstrate the important role of landscape surface cover type to mitigate urban heating by modifying the surface energy balance, especially

during the years after landscape installation but before tree canopies are established to provide maximum shade potential.

DEDICATION

This is for my family, for their unfailing support, love and encouragement. Especially for Meghan and Florian, who learned more about vertical temperature profiles, evapotranspiration and granite mulch than they ever wanted to. Thank you for your guidance and motivation throughout the process.

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In Maricopa County, which contains Phoenix, residential property is the single largest use of developed land, except for agriculture. The residential land-use classification contains more than ten times the number of acres than either commercial or industrial classifications, and previous research has shown that residential land use comprises about 70% of the total land use in the Phoenix metropolitan region (Maricopa Association of Governments, 2004; Stabler, 2003). Sub-classifications break down residential land-use into categories based on number of dwelling units per acre. This classification system does not, however, reflect the variation of landscape designs used in the Phoenix valley.

Because of the overwhelming proportion of land-use dedicated to residential areas, understanding how the environmental factors which influence the UHI are played out in a residential setting is necessary in order to develop ways of mitigating the UHI. However, studying and understanding the UHI in a residential setting proves to be challenging. In contrast to other landscapes, such as municipal street-scapes, public areas or business landscapes, which have more homogeneity within their landscapes, individual homeowners have more control, more options and potentially more involvement in shaping their residential landscapes. Phoenix residential neighborhood landscapes vary in composition from a desert-like landscape with little irrigation to landscapes with varying amounts of turf-grass and low-water use plants to landscapes with extensive turf-grass and large shade trees (Hope et al., 2003; Martin and Stabler, 2004).

Most UHI studies focus on the comparison between urban and rural temperatures, but do little to distinguish among variations within the urban setting, and even less between residential landscape design types. As a result, a major portion of land-use within the urban setting has been understudied. Additionally, most UHI studies obtain data on a large scale. Temperatures are collected largely by using remote sensing for surface temperatures, city-wide meteorological stations, or cross-urban transects (Avissar, 1996; Hedquist and Brazel, 2006; Caparrini et al., 2003; Unger, et al. 2001; Fast et al., 2005; Yuan and Bauer, 2007; Jenerette et al., 2007). One exception is a study by Hartz et al. (2006), which combined several methods of temperature collection to compare surface and air (1.5 m) temperatures in three different Phoenix neighborhoods. In contrast to the present study, however, Hartz et al. (2006) focused primarily on housing density and not landscape design style. As a result, it is unclear how the wide variety of landscape design styles that are implemented in Phoenix residential areas factor into the larger UHI issue.

The wide variety of landscape design styles present in Phoenix are the result of shifting popular attitudes regarding landscape function and resource use. Residential areas built before air conditioning became commonly available in the 1950's featured landscapes comprised extensively of large shade trees, broad leaf shrubbery and flood irrigated lawns. The concentration of water and vegetation in these landscapes utilized high rates of evapotranspirational cooling to mitigate the hot summer conditions (Sailor, 1998). With the increasing

availability of residential air conditioning, public emphasis has shifted away from a landscapes' ability to provide cooling towards reducing water consumption and the preservation of the Sonoran Desert (Larson, et al., 2009; Hurd, 2006; St. Hilaire et al., 2008, Sovocool et al., 2006).

Phoenix's rapid population growth in the last 50 years and concerns regarding water resources has led to a popular effort to find low-water use plants. Landscape vegetation in the Phoenix metropolitan region is normally irrigated because on average the climate of the Sonoran Desert shows an 1843 mm per year evaporation potential deficit (The Arizona Meteorological Network, 2010). It is clear that design styles which feature drought-tolerant plants use less irrigation than the turf grass dominated design styles that had been previously utilized. However, it is unclear how changes in landscape design styles affect other ecological processes and potential benefits derived from more traditional landscapes.

Ecologist have recently started trying to assign a monetary value to the benefits provided by ecological systems, for example, heat mitigation, recreation, air quality restoration, runoff control, wildlife habitat and dust control (Plummer, 2009, Harlan et al., 2006; Akbari et al., 2001, Baker et al., 2002; Pickett et al., 2001, Costanza et al., 1997). However, the environmental and economic benefits provided by urban ecosystems in the southwest have received little attention, despite the fact that the southwest has recently seen some of the highest population growth in the United States. A better understanding of the benefits

and costs of various landscape design styles will help in determining ecologically sustainable landscape designs (Shen et al., 2008; Grimm et al., 2008; Wu, 2007; Golden 2004). One important component of landscape design style is surface cover, because surface cover greatly impacts the amount of heat that enters the soil (Singer and Martin, 2008; Mueller and Day, 2005; Chalker-Scott, 2007). The two major landscape cover types used in Phoenix are turf grass and decomposed granite mulch.

This study seeks to examine the influence of landscape cover type on the surrounding environment at the neighborhood scale. It differs from other studies in two significant ways. First, emphasis is given to landscape design styles as the major difference among treatments. The difference in design styles was reflected mainly in the implantation surface cover, tree and shrub taxa, and irrigation regimes. Secondly, this study examined microclimate variables starting at the surface and extending through the undercanopy profile to a height of 5 m at a fine scale resolution. An analysis of the differences in surface and air temperatures at the neighborhood scale will lead to a better understanding of how landscape choices affect mesoscale climate patterns. This research tested the hypothesis that the mesic and oasis treatments would exhibit distinctly cooler surface and air temperatures among the four tested treatments design styles within 5.0 m above the surface. Additionally, this study tested the hypothesis that observed microclimate effects within the treatments would be more pronounced during premonsoon conditions than during monsoon conditions.

Chapter 2

Material And Methods

The purpose of this research study was to characterize the effect of surface cover as part of landscape design on the microclimate conditions at the neighborhood scale in a Phoenix area residential setting. Four treatment sites, representing four archetypes of landscape design found in the Phoenix metropolitan area, were used to measure surface and air temperatures throughout the day during summer 2007 and winter 2008.

Phoenix weather patterns are dominated by early summer (May through early July) high-pressure systems which lead to hot dry weather, and late summer (mid July through September) monsoon. The thirty-year average high temperature during the month of June is 39.2°C. The thirty-year average high during August, in the middle of the monsoon period, is 40.6°C. The thirty- year average high for February is 21.8°C. (PRISM Climate Group, 2010).

Overall climate conditions of summer 2007 and winter 2008 were typical for the Phoenix valley. The average maximum temperature in June was 39.6° C , which is +0.4°C above the thirty-year average. The average maximum temperature in August was 40.9°C, a difference of +0.3°C from the 30-year average. The average maximum temperature in February was 19.7°C, which is -2.1°C below the thirty-year average (PRISM Climate Group, 2010).

The Phoenix metropolitan area is located in large, wide valley in southern Arizona. It is comprised of several cities, which form a semi-contiguous sprawl of

intermixed urban, residential and industrial areas surrounded by Sonoran desert and irrigated agricultural areas. As the population continues to expand at an increasing rate, urban development encroaches and replaces agricultural fields and virgin desert.

The treatment sites were in an area of student housing located at The Arizona State University Polytechnic campus, which was, until 1997, Williams Air Force Base. Each treatment consisted of six single-story houses, and their associated yards, arranged around a central common area. The houses were constructed during the 1950's and are mostly three bedroom homes with similar floor plans. They were of cement block construction, covered in stucco and painted in earth tones. The common area was separated from the back yards of each house by a concrete path. An asphalt road circumscribed approximately three quarters of the borders of each treatment. Table 1 shows the amount of area covered by homes, hardscape, decomposing granite mulch, turf grass and bare soil in each treatment.

The four treatment sites were landscaped during Spring 2005 as part of the Central Arizona Phoenix Long Term Ecological Research project (CAP LTER). CAP LTER is funded by the National Science Foundation to study urban ecological issues and processes. These four treatment sites were established to provide a controlled residential setting for ecological research at the neighborhood scale. They were planted to reflect archetypes of the four most common landscape design styles found in the Phoenix metropolitan area. Each

Table 1.

Land cover distribution (m^2) of the four residential landscape design treatment areas.

Land cover type	Mesic	Oasis	Treatment Xeric	Desert
Homes	1278	1164	1237	1223
Impervious cover Asphalt concrete walks & carports	547	477	416	422
Pervious cover Decomposing granite	0	3703	4788	4648
Turf grass	3951	442	0	0
Bare soil	0	0	0	0
Total	5776	5786	6441	6293

treatment had plant selection, primary ground cover and irrigation methods similar to local residential landscapes. They were mesic (high water use), oasis (mixed water use), xeric (low water use), and desert (non-irrigated).

The mesic treatment (Fig. 1) was dominated by sprinkler irrigated turf grass, which covered all unpaved areas. Several large extant bottle trees [*Brachychiton populneus* (Schott & Endl.) R. Br.] were left when the treatment was established. A complete list of tree and shrub species can be found on Table 2. Several of the shrub specimens that were planted in the mesic treatment area in 2005 were destroyed by local landscape maintenance personnel who were charged with mowing the turf grass on a weekly basis.

The oasis treatment (Fig. 1) had a drip-irrigated mixture of high and low water use trees and shrubs, and several patches of sprinkler-irrigated turf. One large rectangular turf patch was located in the middle of the common area. Additionally, small patches of turf grass were conjoined to the back-side of each house in the treatment area. A complete list of tree and shrub species can be found on Table 2.

The xeric treatment (Fig. 1) had drip-irrigated low water use trees and shrubs several of which were hybridized varieties of native plants. A complete list of tree and shrub species can be found on Table 2.

The desert treatment (Fig. 1) contained trees, shrubs and cactus species native to the Sonoran desert. Vegetation in the desert treatment were irrigated by garden hose during the first summer after transplanting to facilitate establishment. A

complete list of tree and shrub species can be found on Table 2. All unpaved and non-turf ground surfaces in the oasis, xeric and desert treatment areas were covered in two inches of decomposing granite mulch. The decomposing granite pieces are beige and approximately 9.5 mm in diameter. The albedo of the decomposing granite mulch was 0.16 ± 0.01 (Singer and Martin, 2008).

Regular landscape maintenance, which consisted mainly of mowing and weed control, was provided to all treatments by a commercial landscape maintenance company. Supplemental irrigation provided to the mesic, oasis and xeric treatment areas were scheduled by a Toro Intelli-Sense™ Series controller (The Toro Company, 2010), which regulated watering schedules based on preprogrammed factors including daily evapotranspirational water loss (ET_o), plant type, soil type, and water delivery rate. These controllers received information regarding local evapotranspiration rates via microwave signals from a service provider (Hydro-Point Data Systems, Inc., 2010) and reprogrammed irrigation schedules daily based on ET_o from the previous day.

A mobile meteorological station was constructed to record temperature, percent relative humidity, and saturation vapor pressure conditions throughout the treatments, (Fig. 2). Shielded constantan-copper thermocouples for recording air temperatures were mounted on a pole at heights of 0.25 m, 0.5 m, 1.0 m and 5.0 m. A shielded HMP45C-L probe (Campbell Scientific, Logan UT) was mounted on the same pole at 2.0 m to record air temperature, percent

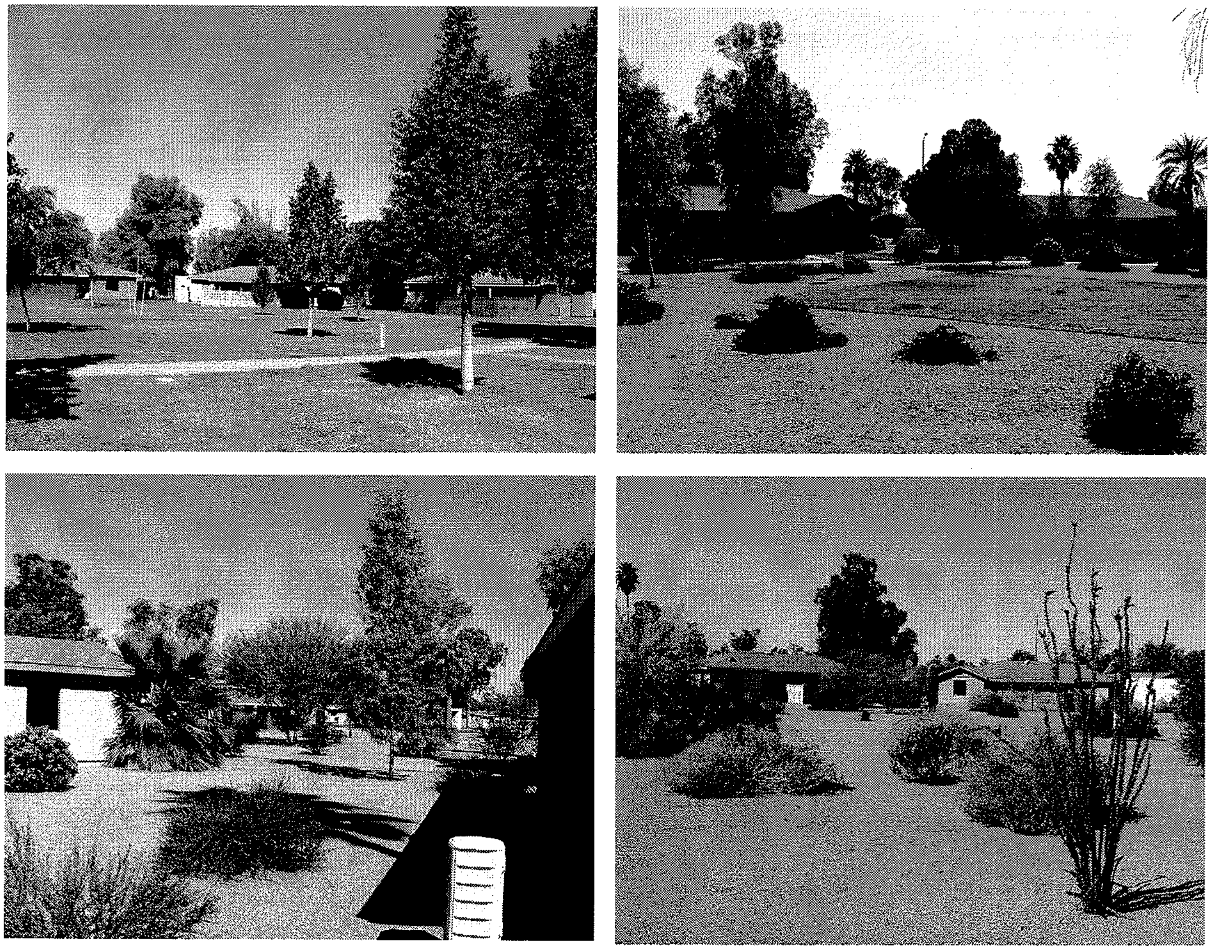

Figure 1. Four North Desert Village residential landscape treatment areas. Images by Chris A. Martin.

Table 2.

List of landscape taxa by scientific^z *and common name (in parenthesis) at North Desert Village residential landscape experimental site (Mesa, Arizona). Landscape taxa are distributed by form (T=Tree, S=Shrub, G=Grass) and landscape design treatment (M=Mesic, O=Oasis, X=Xeric, D=Desert).*

Form	Landscape Taxa	NDV Treatment			
		Mesic	Oasis	Xeric	Desert
T	*Acacia salicina* Lindl. (weeping acacia)		O		
T	*Acacia stenophylla* A. Cunn. ex Benth. (shoestring acacia)		O	X	
S	*Bougainvillea spectabilis* Willd. (bougainvillea)		O		
T	*Brachychiton populneus* Schott & Endl. (bottle tree)	M		X	
T	*Brahea armata* S. Watts (Mexican blue fan palm)			X	
S	*Caesalpinia gilliesii* Wallich ex Hook (desert bird-of-paradise)				D
S	*Caesalpinina pulcherrima* L. (Sw.) (red bird-of-paradise)		O		
S	*Calliandra californica* (Benth.) D. Gibs. (red fairy duster)			X	
S	*Carissa grandiflora* E. H. Mey. (natal plum)		O		
P	*Chamaerops humilis* L. (Mediterranean fan palm)		O		
G	Cynodon dactylon (L.) Pers. (bermuda grass)	M	O		
S	*Encelia farinosa* A. Gray (brittle bush)			X	D
T	*Corymbia papuana* (F. Mueller) K.D. Hill and L.A.S. Johnson (ghost gum)		O		
T	*Eucalyptus polyanthemos* Schauer (silver dollar gum)	M			
S	*Justicia californica* (Benth.) D. Gibs. (chuparosa)				D
S	*Lantana hybrid* L. (lantana)		O		
S	*Larrea tridentata* (DC.) Cov. (creosote bush)				D
S	*Leucophyllum frutescens* (Berland.) I.M. Jonst. (Texas sage)	O	X		
S	*Macfadyena unguis cati* (L.) A. Gentry (cat's claw vine)		O		
T	*Melia azaderach* (L.) (Chinaberry)			X	
S	*Myrtus communis* L. (common myrtle)		O		
S	*Nerium oleander* L. (oleander)	M	O	X	D

T	*Olneya tesota* A. Gray. (desert ironwood)				D
T	*Pinus brutia var eldarica* (Ten.) (Afghan pine)	M	O		
T	*Pistacia chinensis* Bunge. (Chinese pistache)	M			
T	*Platycladus orientalis* (L.) Franco (arborvitae)		O		
T	*Parkinsonia hybrid* (hybrid palo verde)			X	
T	*Parkinsonia florida* (Benth. ex Gray) S. Wats (blue palo verde)				D
T	*Platanus wrightii* P. Watts. (Arizona sycamore)	M			
T	*Prosopis alba x chilensis* Grisebach, (Mol.) Stuntz (South American mesquite)			X	
T	*Prosopis velutina* Woot. (velvet mesquite)				D
S	*Ruellia brittoniana* E. Leonard (common ruellia)		O		
S	*Simmondsia chinensis* (Link) C.K. Schneid (jojoba)				D
T	*Ulmus parvifolia* Jacq. (Chinese elm)	M	O		
T	*Washingtonia filifera* (L. Linden) H. Wendl. (desert fan palm)			X	

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[z] Scientific authority found in Hortus Third (1976).

relative humidity, and saturation vapor pressure. An IRR-PN infrared thermometer (Apogee Instruments, Inc., Logan UT) was mounted at 2.0 m height at a 45° angle to measure ground surface temperature (0.0 m). All measurements were processed with a Campbell Scientific 23X datalogger (Campbell Scientific, Logan, UT) and recorded with a digital voice recorder. Because the impact of the urban heat island on humans is most pronounced during periods of intense summer heat, and Arizona experiences monsoon conditions of elevated atmospheric humidity during the late summer, data were recorded during both June (pre-monsoon) and late August to early September (during monsoon) to compare any influences of the summer monsoon on the neighborhood microclimates. Data were recorded during 900-1000, 1600-1700 and 2100-2200 Hr and took about an entire hour to complete; thus, data was collected from only one treatment area per day. Because of this, all four treatments were measured on near-consecutive days with similar synoptic weather conditions of calm, clear days with daily high temperatures within 3°C. Data were recorded again during February (winter) 2008 to provide comparison between the influence of landscape surface cover during winter and summer. Winter collection times were during 900-1000, 1400-1500 and 2000-2100 Hr. For these reasons, data were collected in all four treatment areas on near-consecutive days with similar anticyclonic synoptic weather conditions of clear, calm days.

Five transects were established in each treatment site, radiating from a common centerpoint and extending into the asphalt street. Weather data were

collected starting with the northernmost transect and proceeding in a clockwise direction. Each transect began with the central starting point, and proceeded at 5 m intervals to the surrounding asphalt street.

Observed temperatures (T_{obs}) were adjusted (T_{adj}) before statistical analysis to compensate for changes in synoptic weather conditions during sample periods of data collection. Synoptic weather conditions were derived from shielded copper constantan thermocouples (2 m height) at fixed micro-meteorological stations positioned near the center of each treatment area.

For each of the five days of sampling during each month, the synoptic ambient air temperature ($Tmet_{mean}$) was estimated as the mean of the air temperatures reported by at the four fixed meteorological stations for the morning, afternoon and evening observation intervals as follows:

$$Tmet_{mean} = (Tmet_{mesic}+Tmet_{oasis} + Tmet_{xeric} + Tmet_{desert})/ 4 \qquad \text{Eq. 1}$$

Next, the greater mean ambient air temperature ($Tmet_{Time}$) for mornings, afternoon and evenings across all four days of sampling was estimated as follows:

$$Tmet_{Time} = [Tmet_{mean(Day1)} + Tmet_{mean(Day2)} + Tmet_{mean(Day3)} + Tmet_{mean(Day4)}] / 4 \qquad \text{Eq. 2}$$

$Tmet_{Time}$ gives an estimation of the mean synoptic ambient temperature during mornings, afternoons or evenings across treatments during each monthly sample period. Adjusted temperatures used for statistical analysis of treatment effects on microclimate were then calculated by subtracting the difference between the $Tmet_{mean}$ and the $Tmet_{Time}$ from T_{obs} as follows:

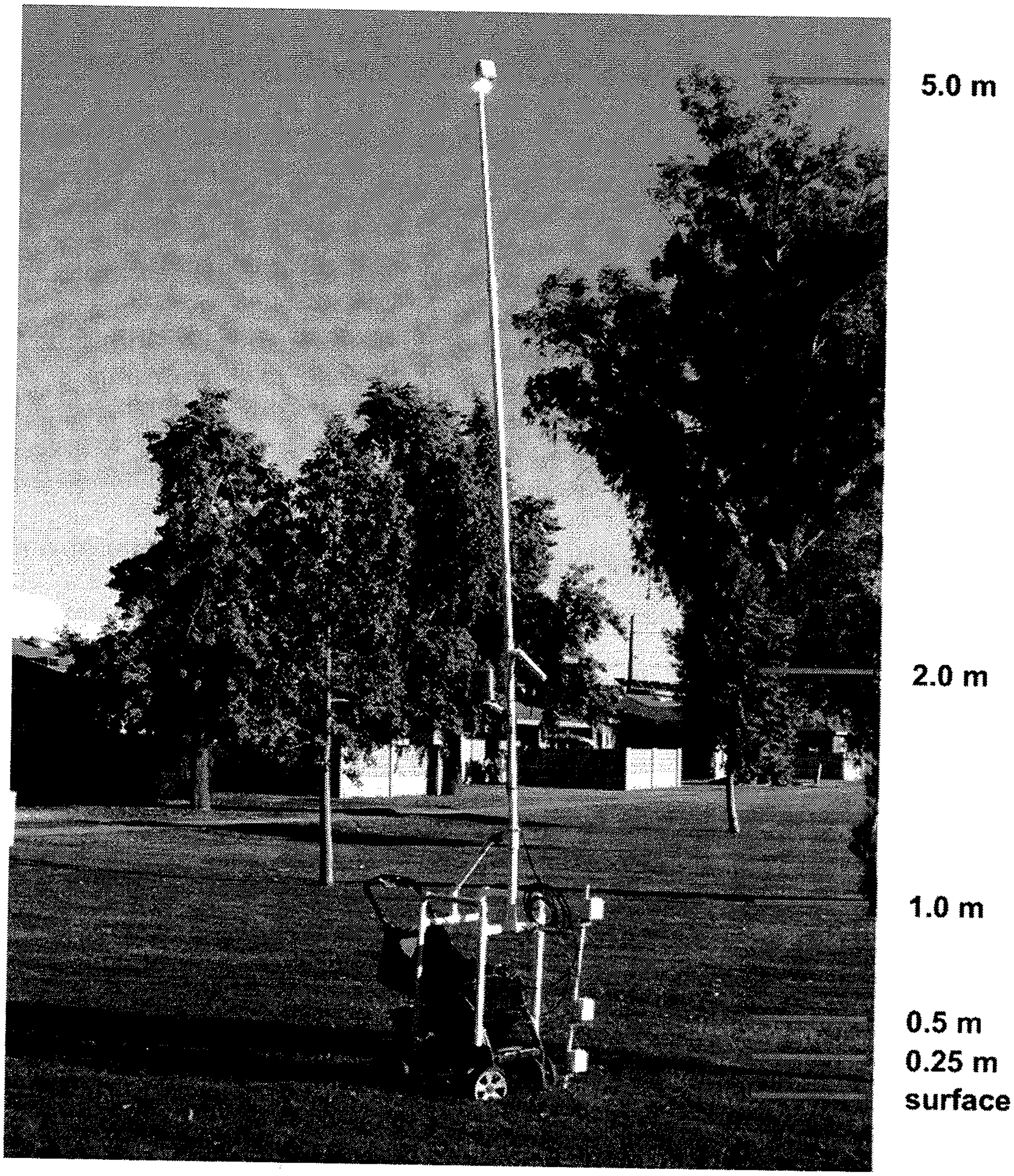


Figure 2. Mobile meteorological station apparatus. Image by Kendra Busse.

$$T_{Adj} = T_{Obs} - (Tmet_{mean} - Tmet_{Time}) \quad \text{Eq. 3}$$

Thus, T_{adj} is an estimate of T_{obs} for each transect point across treatments had it been possible to measure temperatures for all transect within all the treatments simultaneously for each of the three months.

General linear models procedures were used to test for significance of the variables using a split-plot experimental design (JMP 6.0, Cary, NC). Percent relative humidity and saturation vapor pressure deficit (VPD) data were analyzed by landscape design treatments and time of day within month. Mean values were separated by Tukey's HSD test, alpha =0.5. Temperature data were analyzed by landscape design treatments within month and time of day. For temperature data, regression coefficients were tested for homogeneity of fit using the F-test and Mauchley Criterion Sphericity test. Repeated measures analysis using MANOVA was then used to compare vertical height change profiles in temperature as affected by landscape design treatments. Probabilities for the F-test for height and height times treatment interactions for temperature were made using the Greenhouse-Geiser adjustment to univariate *P* values (Littel, 1989). Two dimensional canonical centroid plots by month and time of day showing adjusted treatment least square means and 95% confidence interval ellipses and bi-plot rays for height were generated to show treatment relationships.

Chapter 3

Results

Overall synoptic weather conditions during the data collection periods were not atypical for the Phoenix area. Table 3 indicates summer 2007 was hot with anticyclonic weather patterns with mean daily high temperatures within 3°C. Winter conditions were cooler with somewhat lower atmospheric pressure. Moreover, synoptic weather conditions were somewhat more variable during winter than during the summer periods. Even with the increased atmospheric variability, mean daily high temperatures in Phoenix were within 7°C.

Throughout the collection period, supplemental irrigation was applied to the mesic, oasis and xeric treatments. Figure 3 shows the monthly irrigation volumes applied to each treatment from April 2007 to April 2008.

Pre-monsoon 2007. Repeated measures analyses of data collected during the morning, afternoon, and evening intervals showed that residential landscape design treatments affected temperature height profiles most extensively in the range of 0 to 2 meters above the landscape surface (Fig. 4a-c). For pre-monsoon mornings, canonical centroid plots and test contrasts between the treatments showed a distinct pairing of desert and xeric treatment temperature height profiles (G-G Epsilon P=0.8161) that were both different from the oasis and mesic profiles (G-G Epsilon P=0.0001) (Fig. 4a). Additionally, the mesic and oasis temperature height profiles were significantly different (G-G Epsilon P=0.0008). The greatest difference in adjusted mean temperatures (13°C) was

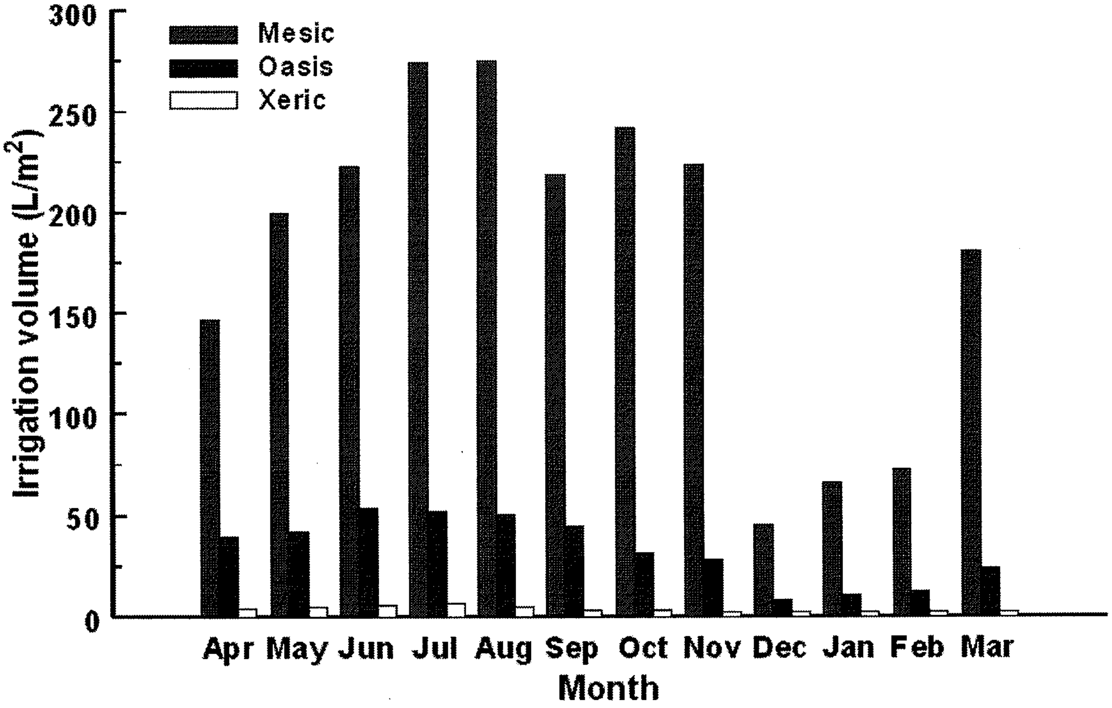
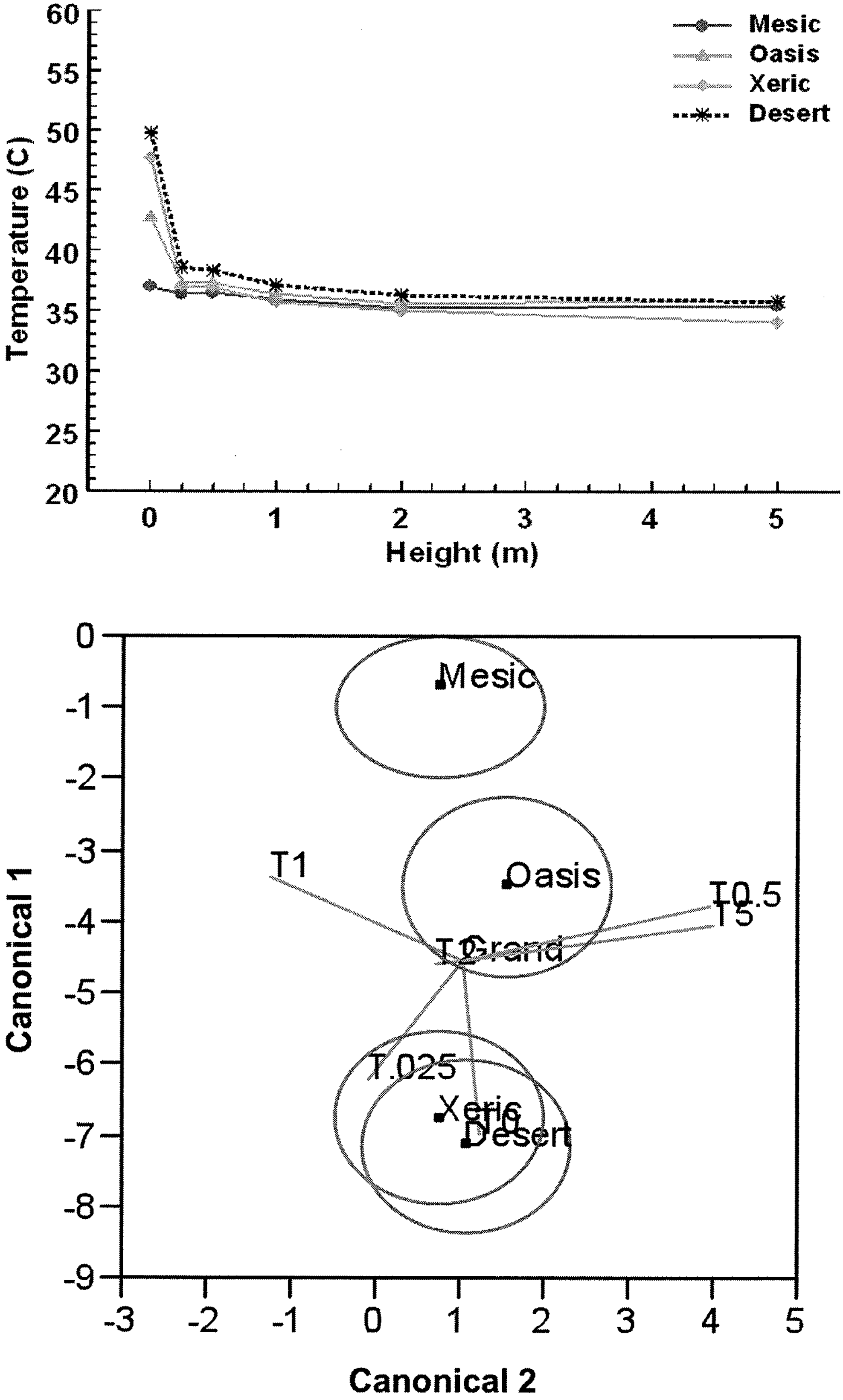


Figure 3. Monthly irrigation volumes applied to landscape design treatments during April 2007 to April 2008. No irrigation was applied to the desert or control treatment areas.

recorded at the landscape surface between the decomposing granite-covered desert (50°C) and turf grass-covered mesic (37°C) treatments. In contrast, treatment-related differences in adjusted mean air temperatures between 0.25 m and 5 m above the surface were 2°C or less. A similarity in the direction of biplot rays within canonical space for height variables during pre-monsoon mornings was detected for the 0.5-m and 5-m heights (Fig. 4a). Across the treatments, morning mean relative humidities and saturation vapor pressures at 2-m height ranged from 11.4% (oasis) to 13.8% (xeric) and 7.13 to 8.19 KPa, respectively (Table 4).

For the pre-monsoon afternoon, canonical centroid plots and test contrasts between the treatments showed a distinct pairing of desert and xeric treatment temperature height profiles (G-G Epsilon P=0.4756) that were both different from the oasis (G-G Epsilon P=0.007) and mesic (G-G Epsilon P=0.0001) temperature height profiles (Fig. 4b). Additionally, the mesic and oasis temperature height profiles were significantly different (G-G Epsilon P=0.0001). Similar to the pre-monsoon morning data, the greatest difference in adjusted mean temperature (22°C) during pre-monsoon afternoons was recorded at the landscape surface between the desert (55°C) and mesic (33°C) treatments. The treatment-related differences in adjusted mean temperatures between 0.025 m and 5 m ranged from approximately 4°C to less than 2°C. For pre-monsoon afternoons, a similarity in the direction in canonical space of biplot rays for height variables was detected for the surface and 0.5-m heights (Fig. 4b). Across

Figure 4a.


Mesic
Oasis
Xeric
Desert
Temperature (C)
60
55
50
45
40
35
30
25
20
0
1
2
3
4
5
Height (m)
Mesic
Oasis
Xeric
Desert
T1
T0.5
T5
T2
Grand
T.025
T0
Canonical 1
0
-1
-2
-3
-4
-5
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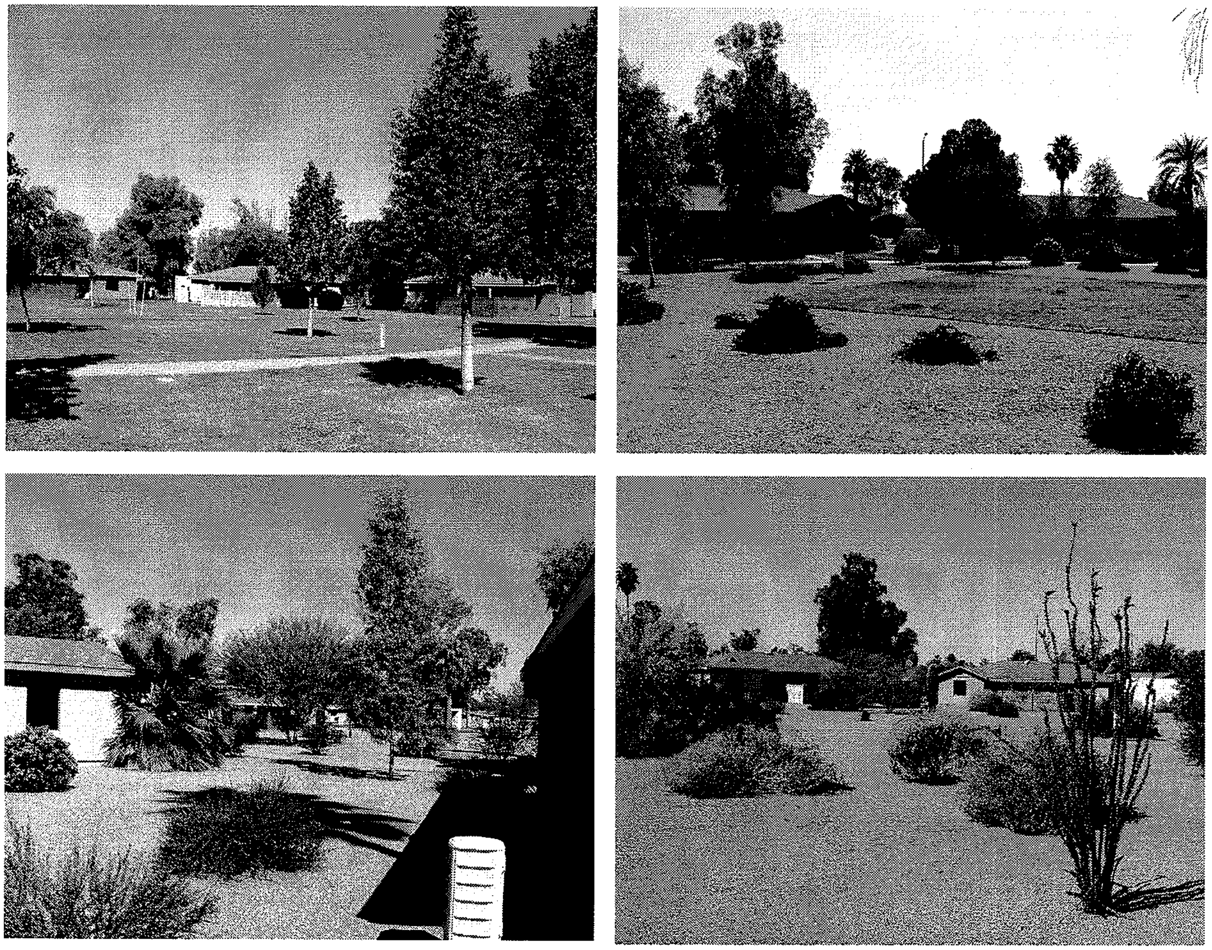
Canonical 2



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Form	Landscape Taxa	NDV Treatment			
		Mesic	Oasis	Xeric	Desert
T	*Acacia salicina* Lindl. (weeping acacia)		O		
T	*Acacia stenophylla* A. Cunn. ex Benth. (shoestring acacia)		O	X	
S	*Bougainvillea spectabilis* Willd. (bougainvillea)		O		
T	*Brachychiton populneus* Schott & Endl. (bottle tree)	M		X	
T	*Brahea armata* S. Watts (Mexican blue fan palm)			X	
S	*Caesalpinia gilliesii* Wallich ex Hook (desert bird-of-paradise)				D
S	*Caesalpinina pulcherrima* L. (Sw.) (red bird-of-paradise)		O		
S	*Calliandra californica* (Benth.) D. Gibs. (red fairy duster)			X	
S	*Carissa grandiflora* E. H. Mey. (natal plum)		O		
P	*Chamaerops humilis* L. (Mediterranean fan palm)		O		
G	Cynodon dactylon (L.) Pers. (bermuda grass)	M	O		
S	*Encelia farinosa* A. Gray (brittle bush)			X	D
T	*Corymbia papuana* (F. Mueller) K.D. Hill and L.A.S. Johnson (ghost gum)		O		
T	*Eucalyptus polyanthemos* Schauer (silver dollar gum)	M			
S	*Justicia californica* (Benth.) D. Gibs. (chuparosa)				D
S	*Lantana hybrid* L. (lantana)		O		
S	*Larrea tridentata* (DC.) Cov. (creosote bush)				D
S	*Leucophyllum frutescens* (Berland.) I.M. Jonst. (Texas sage)	O	X		
S	*Macfadyena unguis cati* (L.) A. Gentry (cat's claw vine)		O		
T	*Melia azaderach* (L.) (Chinaberry)			X	
S	*Myrtus communis* L. (common myrtle)		O		
S	*Nerium oleander* L. (oleander)	M	O	X	D

T	*Olneya tesota* A. Gray. (desert ironwood)				D
T	*Pinus brutia var eldarica* (Ten.) (Afghan pine)	M	O		
T	*Pistacia chinensis* Bunge. (Chinese pistache)	M			
T	*Platycladus orientalis* (L.) Franco (arborvitae)		O		
T	*Parkinsonia hybrid* (hybrid palo verde)			X	
T	*Parkinsonia florida* (Benth. ex Gray) S. Wats (blue palo verde)				D
T	*Platanus wrightii* P. Watts. (Arizona sycamore)	M			
T	*Prosopis alba x chilensis* Grisebach, (Mol.) Stuntz (South American mesquite)			X	
T	*Prosopis velutina* Woot. (velvet mesquite)				D
S	*Ruellia brittoniana* E. Leonard (common ruellia)		O		
S	*Simmondsia chinensis* (Link) C.K. Schneid (jojoba)				D
T	*Ulmus parvifolia* Jacq. (Chinese elm)	M	O		
T	*Washingtonia filifera* (L. Linden) H. Wendl. (desert fan palm)			X	

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[z] Scientific authority found in Hortus Third (1976).

relative humidity, and saturation vapor pressure. An IRR-PN infrared thermometer (Apogee Instruments, Inc., Logan UT) was mounted at 2.0 m height at a 45° angle to measure ground surface temperature (0.0 m). All measurements were processed with a Campbell Scientific 23X datalogger (Campbell Scientific, Logan, UT) and recorded with a digital voice recorder. Because the impact of the urban heat island on humans is most pronounced during periods of intense summer heat, and Arizona experiences monsoon conditions of elevated atmospheric humidity during the late summer, data were recorded during both June (pre-monsoon) and late August to early September (during monsoon) to compare any influences of the summer monsoon on the neighborhood microclimates. Data were recorded during 900-1000, 1600-1700 and 2100-2200 Hr and took about an entire hour to complete; thus, data was collected from only one treatment area per day. Because of this, all four treatments were measured on near-consecutive days with similar synoptic weather conditions of calm, clear days with daily high temperatures within 3°C. Data were recorded again during February (winter) 2008 to provide comparison between the influence of landscape surface cover during winter and summer. Winter collection times were during 900-1000, 1400-1500 and 2000-2100 Hr. For these reasons, data were collected in all four treatment areas on near-consecutive days with similar anticyclonic synoptic weather conditions of clear, calm days.

Five transects were established in each treatment site, radiating from a common centerpoint and extending into the asphalt street. Weather data were

collected starting with the northernmost transect and proceeding in a clockwise direction. Each transect began with the central starting point, and proceeded at 5 m intervals to the surrounding asphalt street.

Observed temperatures (T_{obs}) were adjusted (T_{adj}) before statistical analysis to compensate for changes in synoptic weather conditions during sample periods of data collection. Synoptic weather conditions were derived from shielded copper constantan thermocouples (2 m height) at fixed micro-meteorological stations positioned near the center of each treatment area.

For each of the five days of sampling during each month, the synoptic ambient air temperature ($Tmet_{mean}$) was estimated as the mean of the air temperatures reported by at the four fixed meteorological stations for the morning, afternoon and evening observation intervals as follows:

$$Tmet_{mean} = (Tmet_{mesic}+Tmet_{oasis} + Tmet_{xeric} + Tmet_{desert})/ 4 \qquad \text{Eq. 1}$$

Next, the greater mean ambient air temperature ($Tmet_{Time}$) for mornings, afternoon and evenings across all four days of sampling was estimated as follows:

$$Tmet_{Time} = [Tmet_{mean(Day1)} + Tmet_{mean(Day2)} + Tmet_{mean(Day3)} + Tmet_{mean(Day4)}] / 4 \qquad \text{Eq. 2}$$

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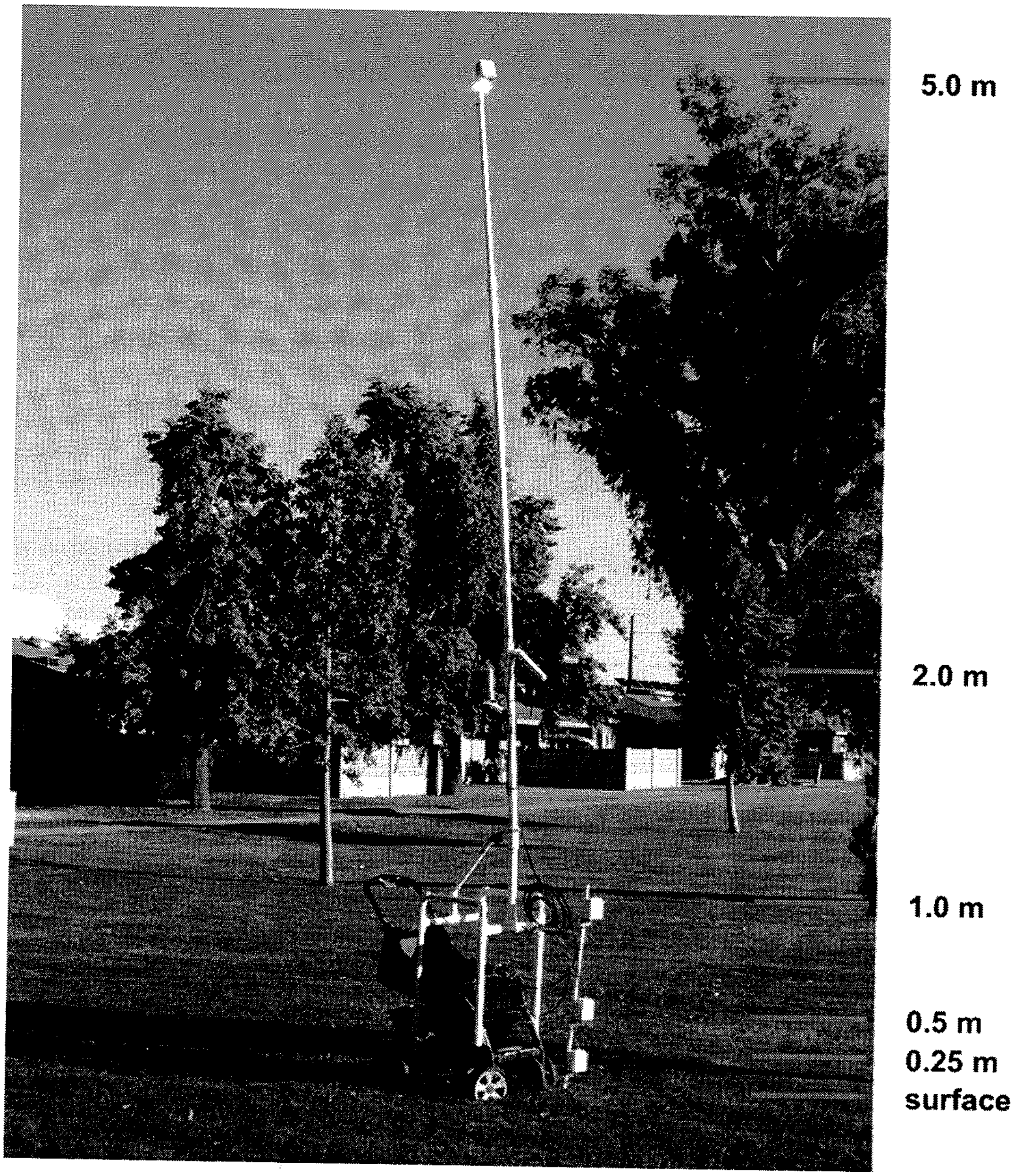

Figure 2. Mobile meteorological station apparatus. Image by Kendra Busse.

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Thus, T_{adj} is an estimate of T_{obs} for each transect point across treatments had it been possible to measure temperatures for all transect within all the treatments simultaneously for each of the three months.

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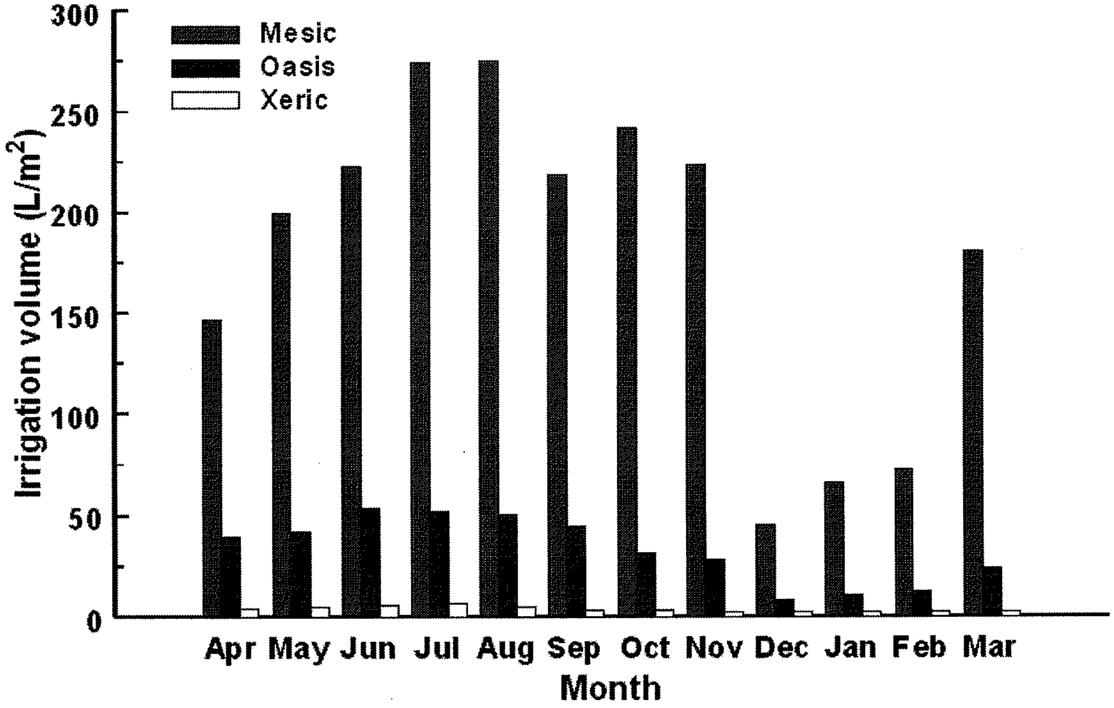

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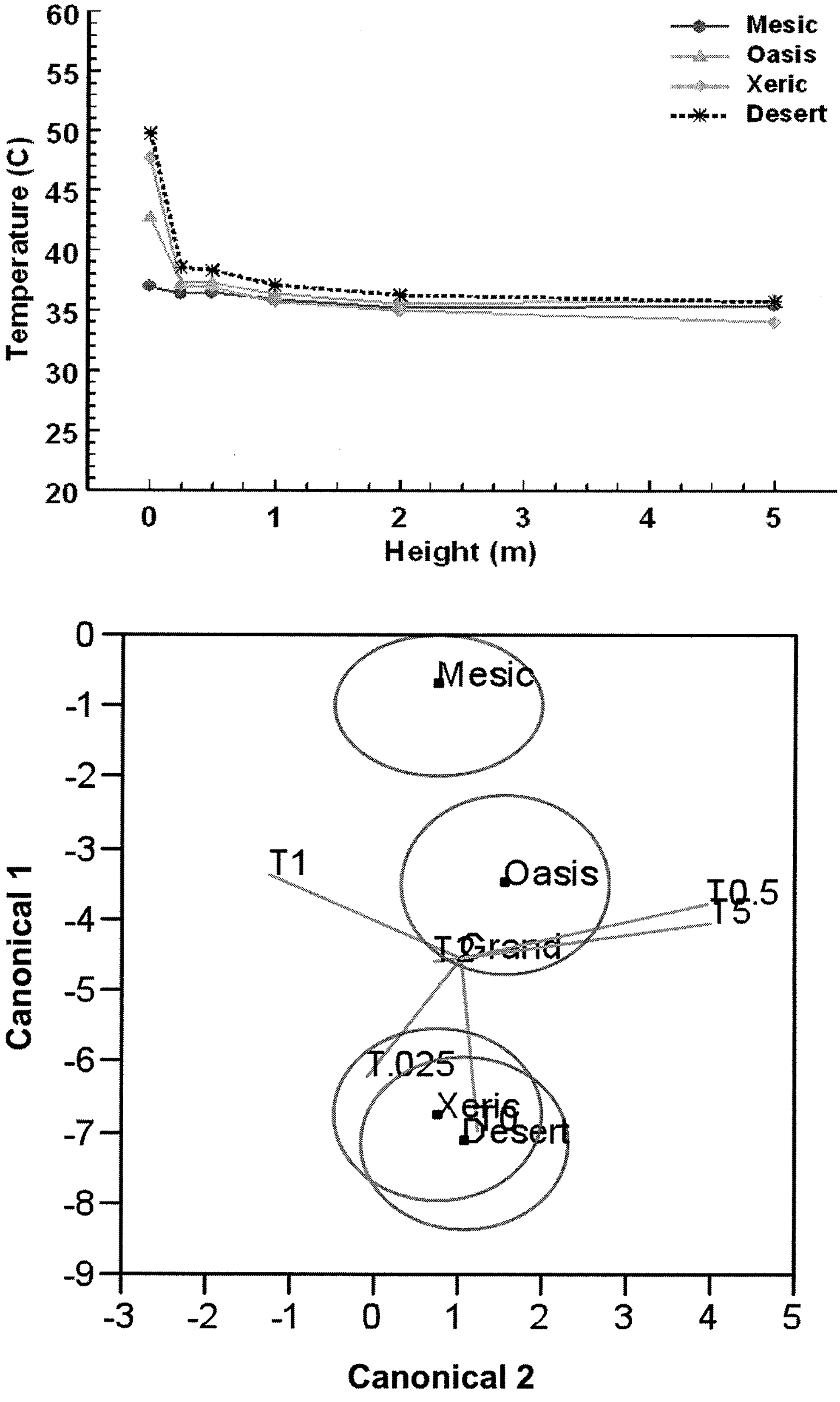
recorded at the landscape surface between the decomposing granite-covered desert (50°C) and turf grass-covered mesic (37°C) treatments. In contrast, treatment-related differences in adjusted mean air temperatures between 0.25 m and 5 m above the surface were 2°C or less. A similarity in the direction of biplot rays within canonical space for height variables during pre-monsoon mornings was detected for the 0.5-m and 5-m heights (Fig. 4a). Across the treatments, morning mean relative humidities and saturation vapor pressures at 2-m height ranged from 11.4% (oasis) to 13.8% (xeric) and 7.13 to 8.19 KPa, respectively (Table 4).

For the pre-monsoon afternoon, canonical centroid plots and test contrasts between the treatments showed a distinct pairing of desert and xeric treatment temperature height profiles (G-G Epsilon P=0.4756) that were both different from the oasis (G-G Epsilon P=0.007) and mesic (G-G Epsilon P=0.0001) temperature height profiles (Fig. 4b). Additionally, the mesic and oasis temperature height profiles were significantly different (G-G Epsilon P=0.0001). Similar to the pre-monsoon morning data, the greatest difference in adjusted mean temperature (22°C) during pre-monsoon afternoons was recorded at the landscape surface between the desert (55°C) and mesic (33°C) treatments. The treatment-related differences in adjusted mean temperatures between 0.025 m and 5 m ranged from approximately 4°C to less than 2°C. For pre-monsoon afternoons, a similarity in the direction in canonical space of biplot rays for height variables was detected for the surface and 0.5-m heights (Fig. 4b). Across

Figure 4a.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Oasis
Xeric
Desert
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40
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25
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1
2
3
4
5
Height (m)
Mesic
Oasis
T1
T0.5
T5
T2
Grand
T.025
Xeric
T0
Desert
Canonical 1
0
-1
-2
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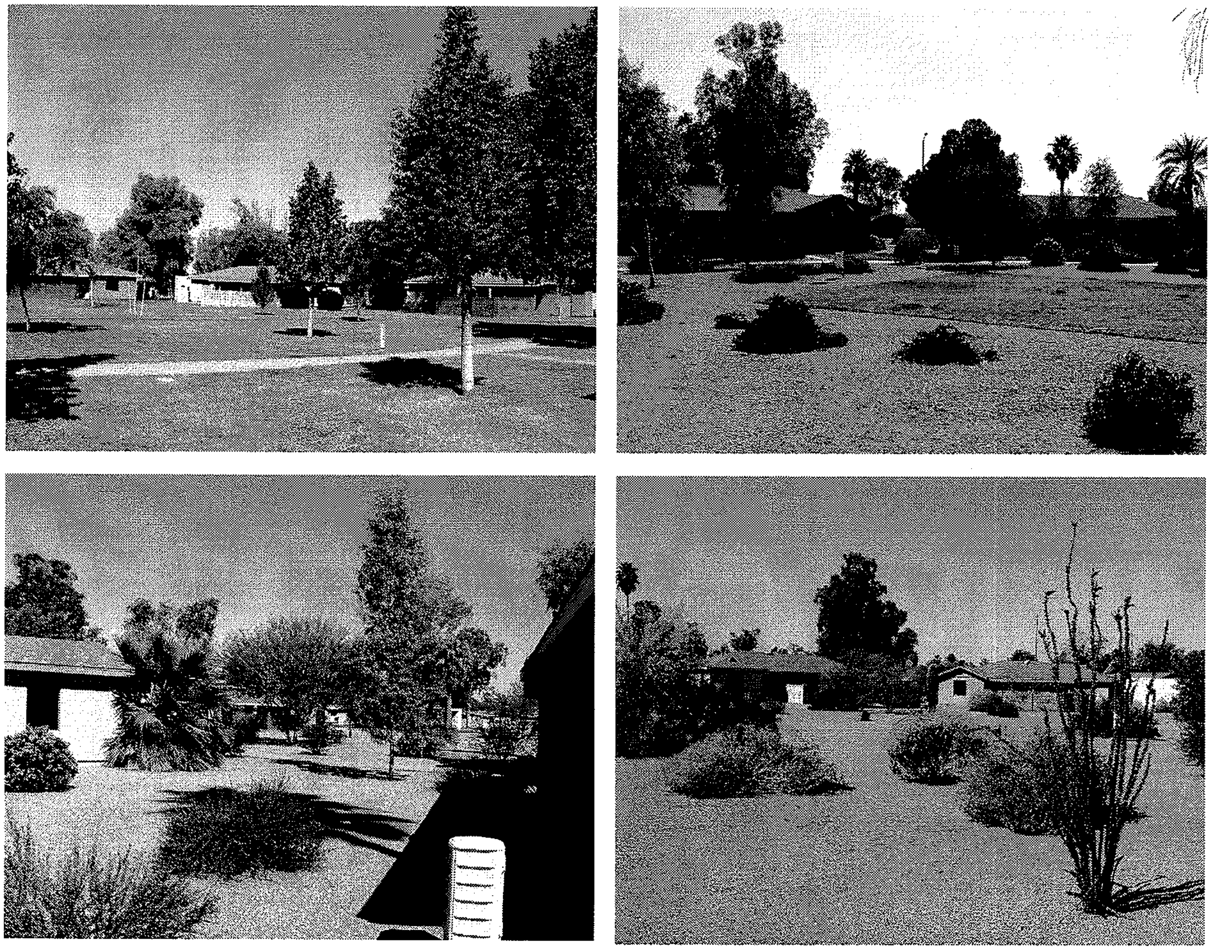

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Form	Landscape Taxa	NDV Treatment			
		Mesic	Oasis	Xeric	Desert
T	*Acacia salicina* Lindl. (weeping acacia)		O		
T	*Acacia stenophylla* A. Cunn. ex Benth. (shoestring acacia)		O	X	
S	*Bougainvillea spectabilis* Willd. (bougainvillea)		O		
T	*Brachychiton populneus* Schott & Endl. (bottle tree)	M		X	
T	*Brahea armata* S. Watts (Mexican blue fan palm)			X	
S	*Caesalpinia gilliesii* Wallich ex Hook (desert bird-of-paradise)				D
S	*Caesalpinina pulcherrima* L. (Sw.) (red bird-of-paradise)		O		
S	*Calliandra californica* (Benth.) D. Gibs. (red fairy duster)			X	
S	*Carissa grandiflora* E. H. Mey. (natal plum)		O		
P	*Chamaerops humilis* L. (Mediterranean fan palm)		O		
G	Cynodon dactylon (L.) Pers. (bermuda grass)	M	O		
S	*Encelia farinosa* A. Gray (brittle bush)			X	D
T	*Corymbia papuana* (F. Mueller) K.D. Hill and L.A.S. Johnson (ghost gum)		O		
T	*Eucalyptus polyanthemos* Schauer (silver dollar gum)	M			
S	*Justicia californica* (Benth.) D. Gibs. (chuparosa)				D
S	*Lantana hybrid* L. (lantana)		O		
S	*Larrea tridentata* (DC.) Cov. (creosote bush)				D
S	*Leucophyllum frutescens* (Berland.) I.M. Jonst. (Texas sage)	O	X		
S	*Macfadyena unguis cati* (L.) A. Gentry (cat's claw vine)		O		
T	*Melia azaderach* (L.) (Chinaberry)			X	
S	*Myrtus communis* L. (common myrtle)		O		
S	*Nerium oleander* L. (oleander)	M	O	X	D

T	*Olneya tesota* A. Gray. (desert ironwood)				D
T	*Pinus brutia var eldarica* (Ten.) (Afghan pine)	M	O		
T	*Pistacia chinensis* Bunge. (Chinese pistache)	M			
T	*Platycladus orientalis* (L.) Franco (arborvitae)		O		
T	*Parkinsonia hybrid* (hybrid palo verde)			X	
T	*Parkinsonia florida* (Benth. ex Gray) S. Wats (blue palo verde)				D
T	*Platanus wrightii* P. Watts. (Arizona sycamore)	M			
T	*Prosopis alba x chilensis* Grisebach, (Mol.) Stuntz (South American mesquite)			X	
T	*Prosopis velutina* Woot. (velvet mesquite)				D
S	*Ruellia brittoniana* E. Leonard (common ruellia)		O		
S	*Simmondsia chinensis* (Link) C.K. Schneid (jojoba)				D
T	*Ulmus parvifolia* Jacq. (Chinese elm)	M	O		
T	*Washingtonia filifera* (L. Linden) H. Wendl. (desert fan palm)			X	

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relative humidity, and saturation vapor pressure. An IRR-PN infrared thermometer (Apogee Instruments, Inc., Logan UT) was mounted at 2.0 m height at a 45° angle to measure ground surface temperature (0.0 m). All measurements were processed with a Campbell Scientific 23X datalogger (Campbell Scientific, Logan, UT) and recorded with a digital voice recorder. Because the impact of the urban heat island on humans is most pronounced during periods of intense summer heat, and Arizona experiences monsoon conditions of elevated atmospheric humidity during the late summer, data were recorded during both June (pre-monsoon) and late August to early September (during monsoon) to compare any influences of the summer monsoon on the neighborhood microclimates. Data were recorded during 900-1000, 1600-1700 and 2100-2200 Hr and took about an entire hour to complete; thus, data was collected from only one treatment area per day. Because of this, all four treatments were measured on near-consecutive days with similar synoptic weather conditions of calm, clear days with daily high temperatures within 3°C. Data were recorded again during February (winter) 2008 to provide comparison between the influence of landscape surface cover during winter and summer. Winter collection times were during 900-1000, 1400-1500 and 2000-2100 Hr. For these reasons, data were collected in all four treatment areas on near-consecutive days with similar anticyclonic synoptic weather conditions of clear, calm days.

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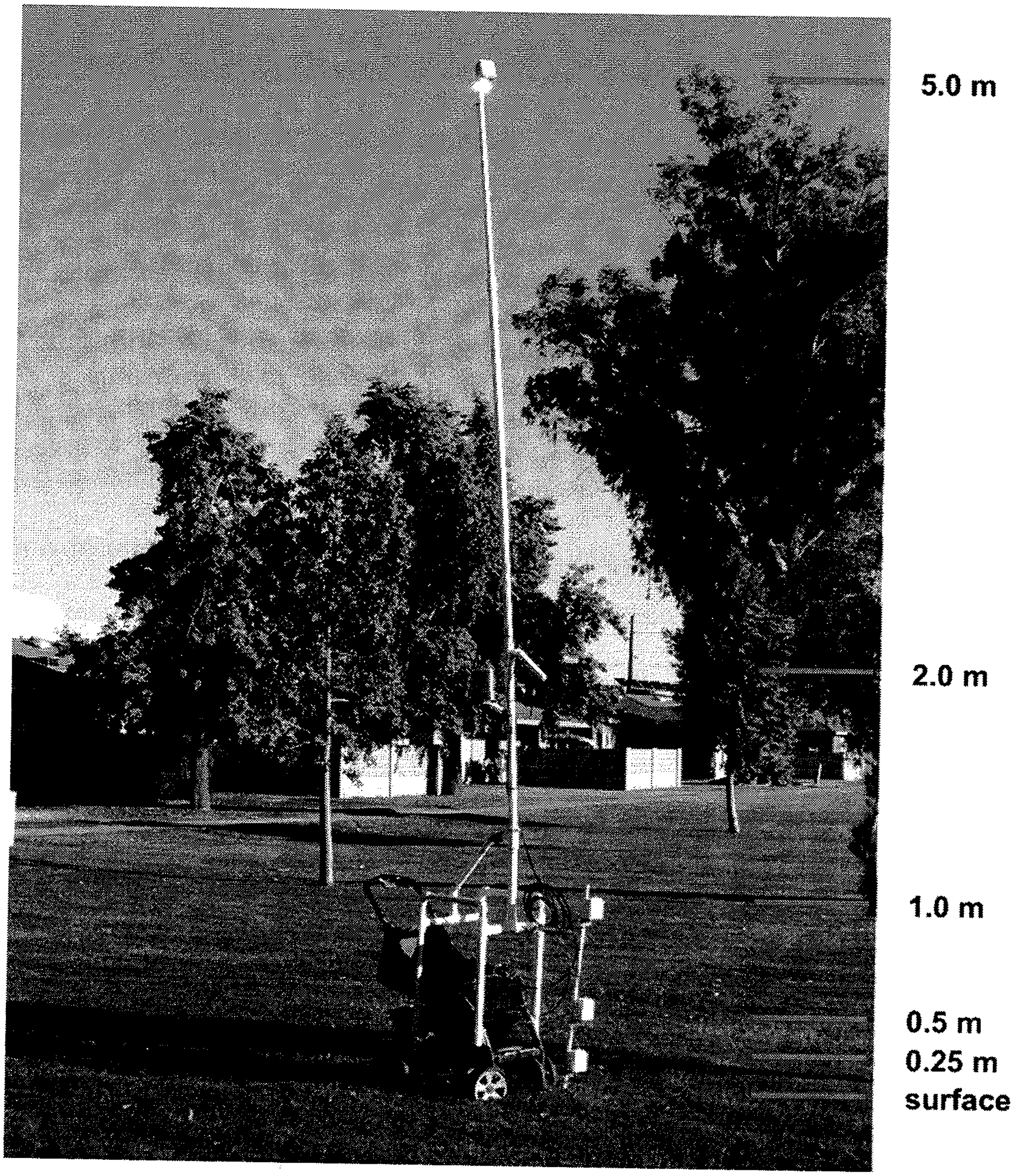

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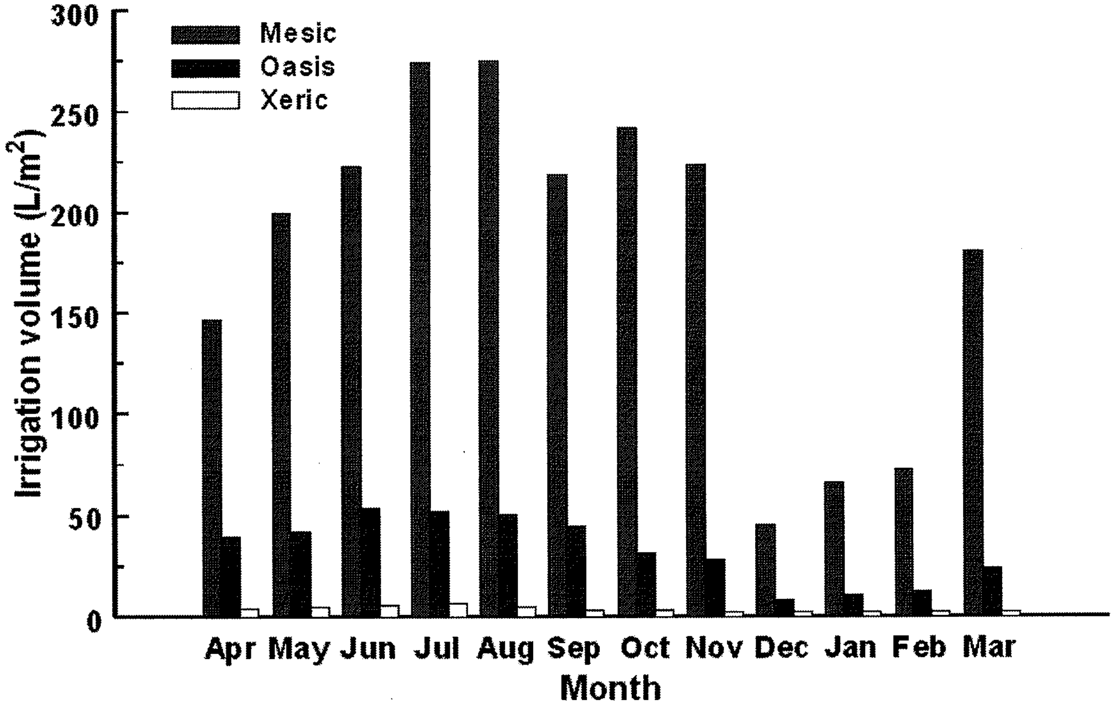

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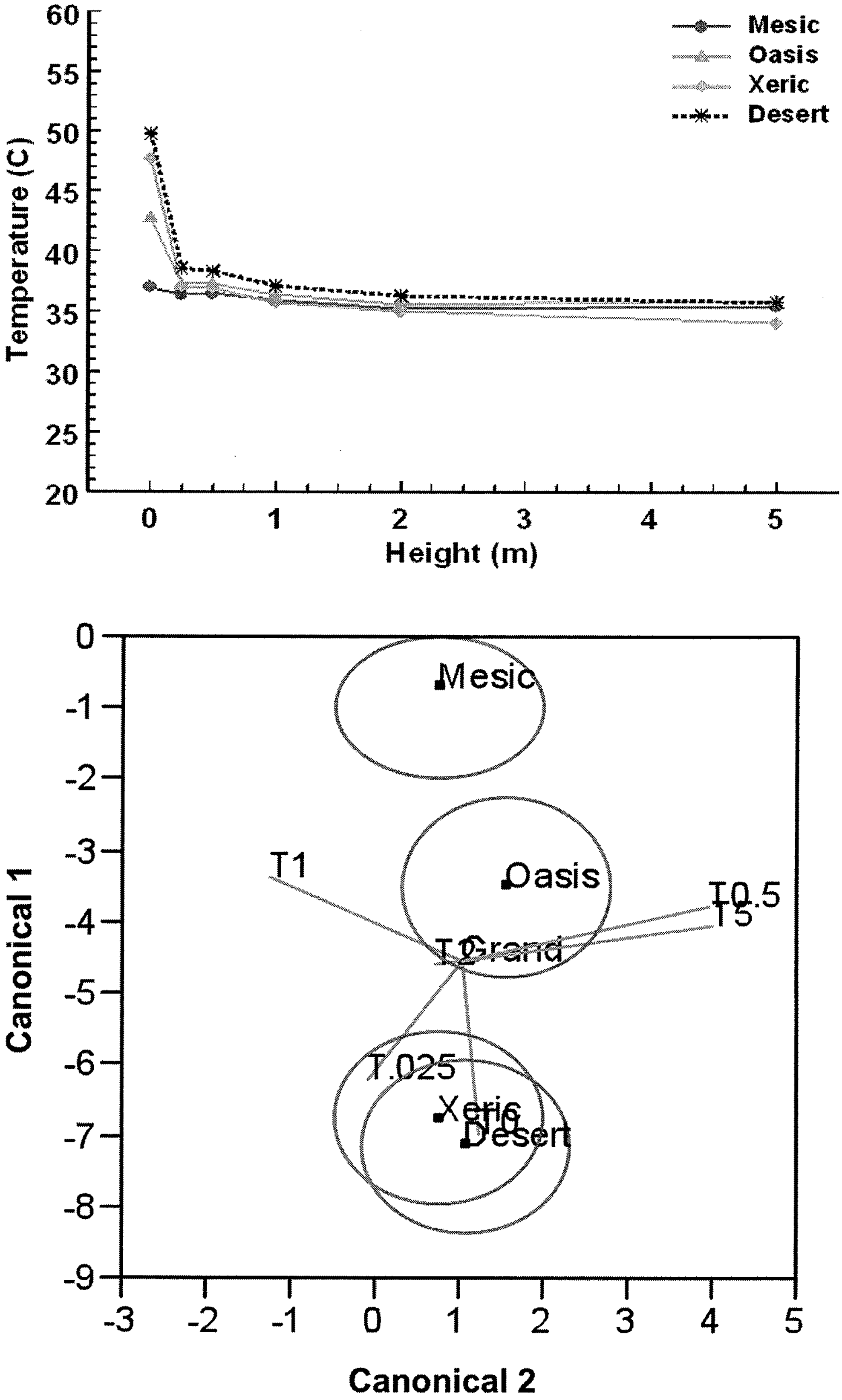
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45
40
35
30
25
20
Height (m)
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1
2
3
4
5
Mesic
Oasis
Xeric
Desert
Canonical 1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
Canonical 2
-3
-2
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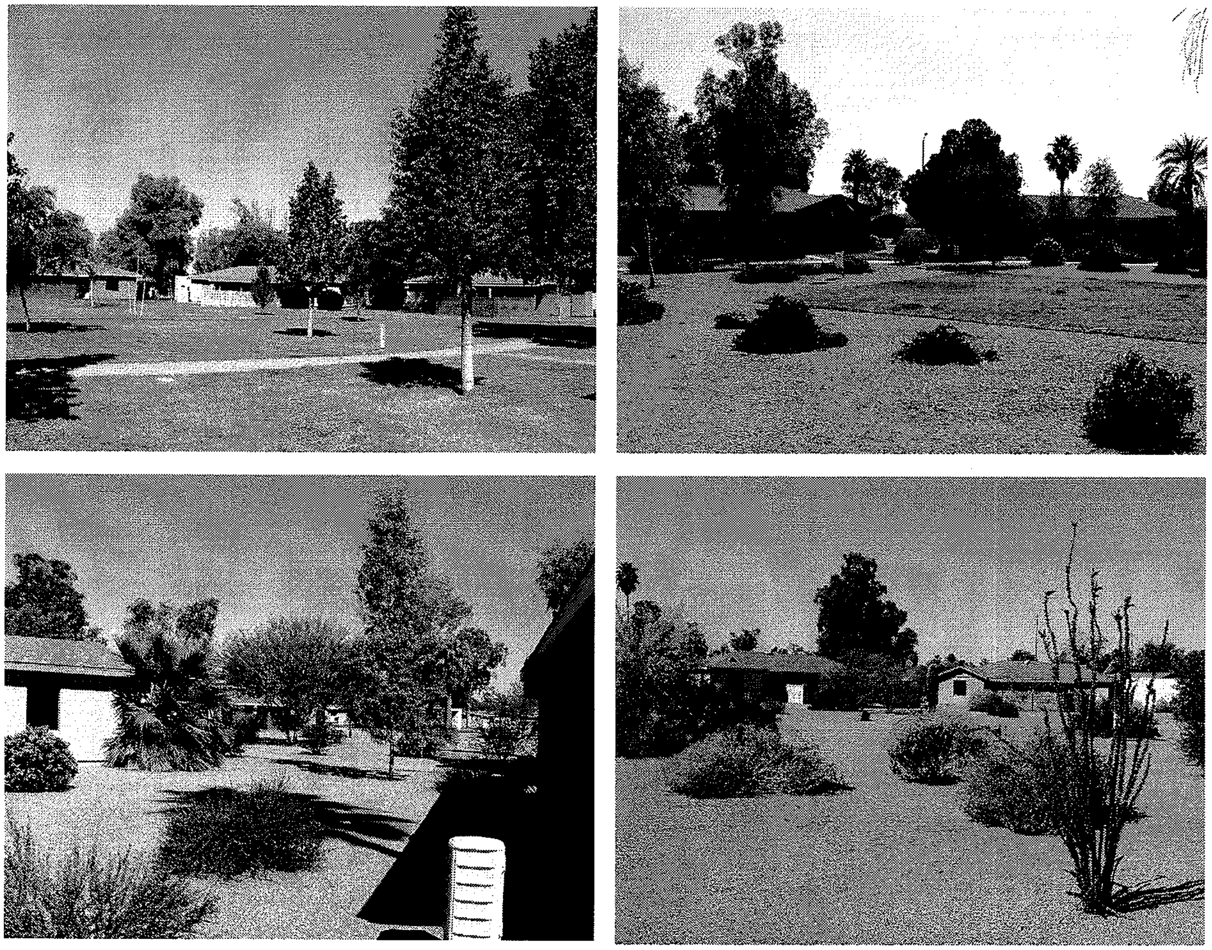

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T	*Brachychiton populneus* Schott & Endl. (bottle tree)	M		X	
T	*Brahea armata* S. Watts (Mexican blue fan palm)			X	
S	*Caesalpinia gilliesii* Wallich ex Hook (desert bird-of-paradise)				D
S	*Caesalpinina pulcherrima* L. (Sw.) (red bird-of-paradise)		O		
S	*Calliandra californica* (Benth.) D. Gibs. (red fairy duster)			X	
S	*Carissa grandiflora* E. H. Mey. (natal plum)		O		
P	*Chamaerops humilis* L. (Mediterranean fan palm)		O		
G	Cynodon dactylon (L.) Pers. (bermuda grass)	M	O		
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S	*Larrea tridentata* (DC.) Cov. (creosote bush)				D
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T	*Melia azaderach* (L.) (Chinaberry)			X	
S	*Myrtus communis* L. (common myrtle)		O		
S	*Nerium oleander* L. (oleander)	M	O	X	D

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T	*Pinus brutia var eldarica* (Ten.) (Afghan pine)	M	O		
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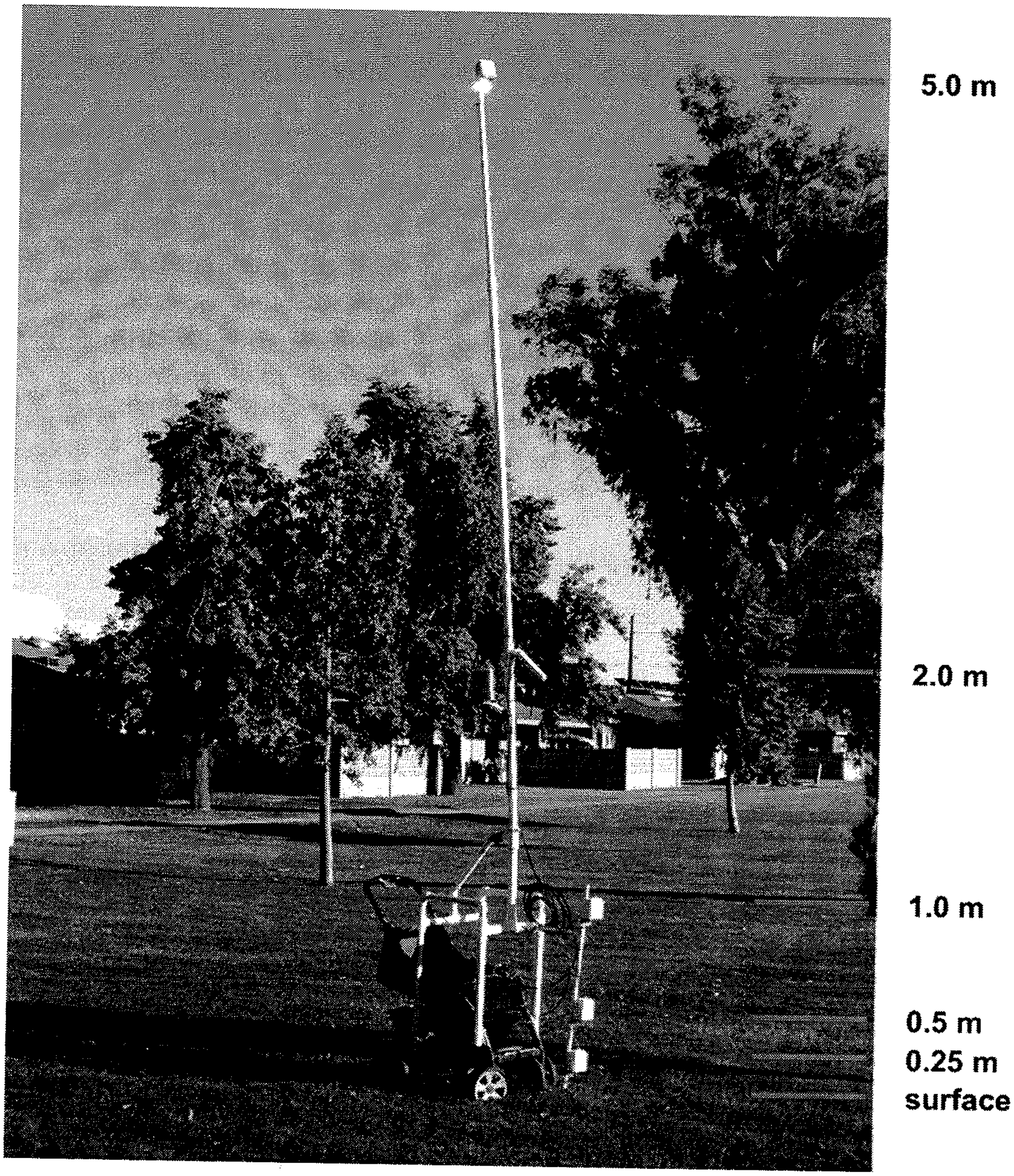

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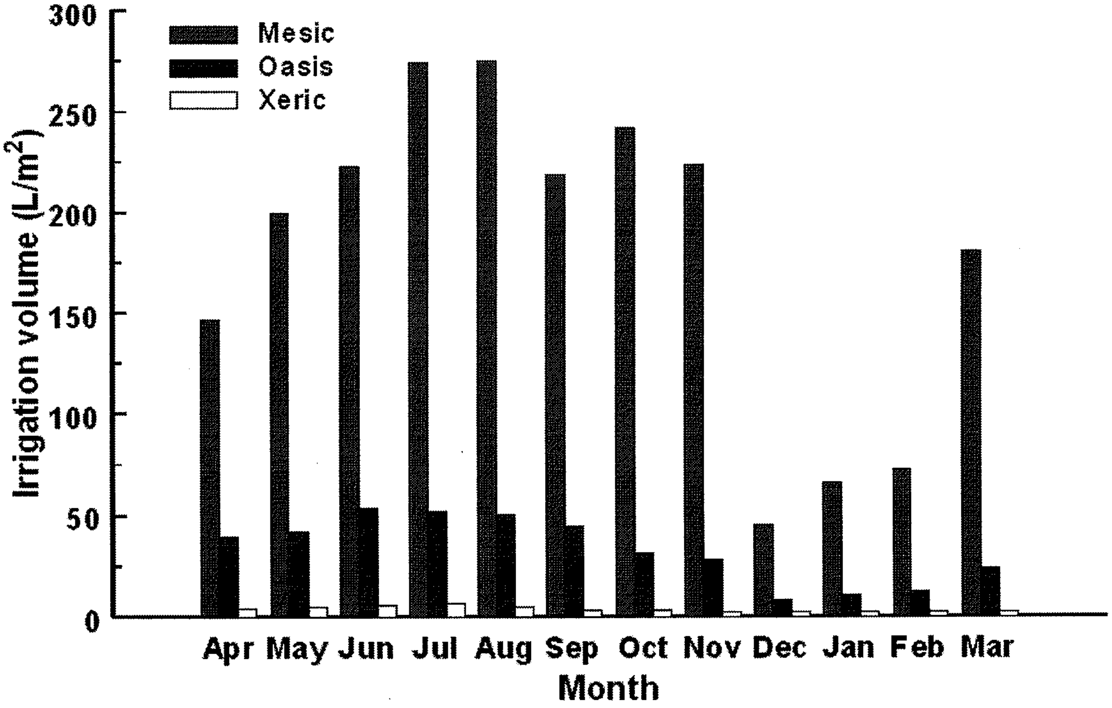
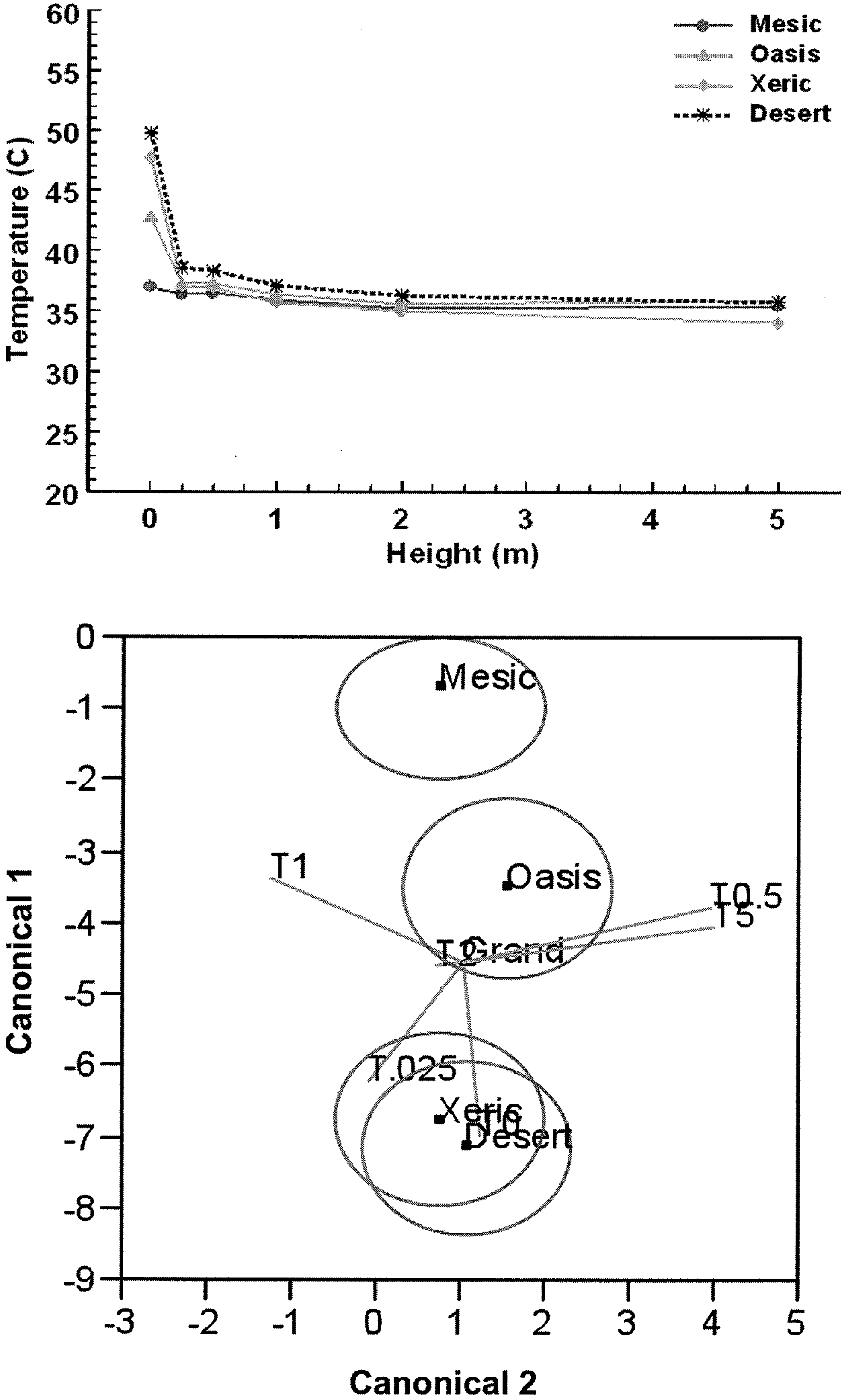


Figure 3. Monthly irrigation volumes applied to landscape design treatments during April 2007 to April 2008. No irrigation was applied to the desert or control treatment areas.

recorded at the landscape surface between the decomposing granite-covered desert (50°C) and turf grass-covered mesic (37°C) treatments. In contrast, treatment-related differences in adjusted mean air temperatures between 0.25 m and 5 m above the surface were 2°C or less. A similarity in the direction of biplot rays within canonical space for height variables during pre-monsoon mornings was detected for the 0.5-m and 5-m heights (Fig. 4a). Across the treatments, morning mean relative humidities and saturation vapor pressures at 2-m height ranged from 11.4% (oasis) to 13.8% (xeric) and 7.13 to 8.19 KPa, respectively (Table 4).

For the pre-monsoon afternoon, canonical centroid plots and test contrasts between the treatments showed a distinct pairing of desert and xeric treatment temperature height profiles (G-G Epsilon P=0.4756) that were both different from the oasis (G-G Epsilon P=0.007) and mesic (G-G Epsilon P=0.0001) temperature height profiles (Fig. 4b). Additionally, the mesic and oasis temperature height profiles were significantly different (G-G Epsilon P=0.0001). Similar to the pre-monsoon morning data, the greatest difference in adjusted mean temperature (22°C) during pre-monsoon afternoons was recorded at the landscape surface between the desert (55°C) and mesic (33°C) treatments. The treatment-related differences in adjusted mean temperatures between 0.025 m and 5 m ranged from approximately 4°C to less than 2°C. For pre-monsoon afternoons, a similarity in the direction in canonical space of biplot rays for height variables was detected for the surface and 0.5-m heights (Fig. 4b). Across

Figure 4a.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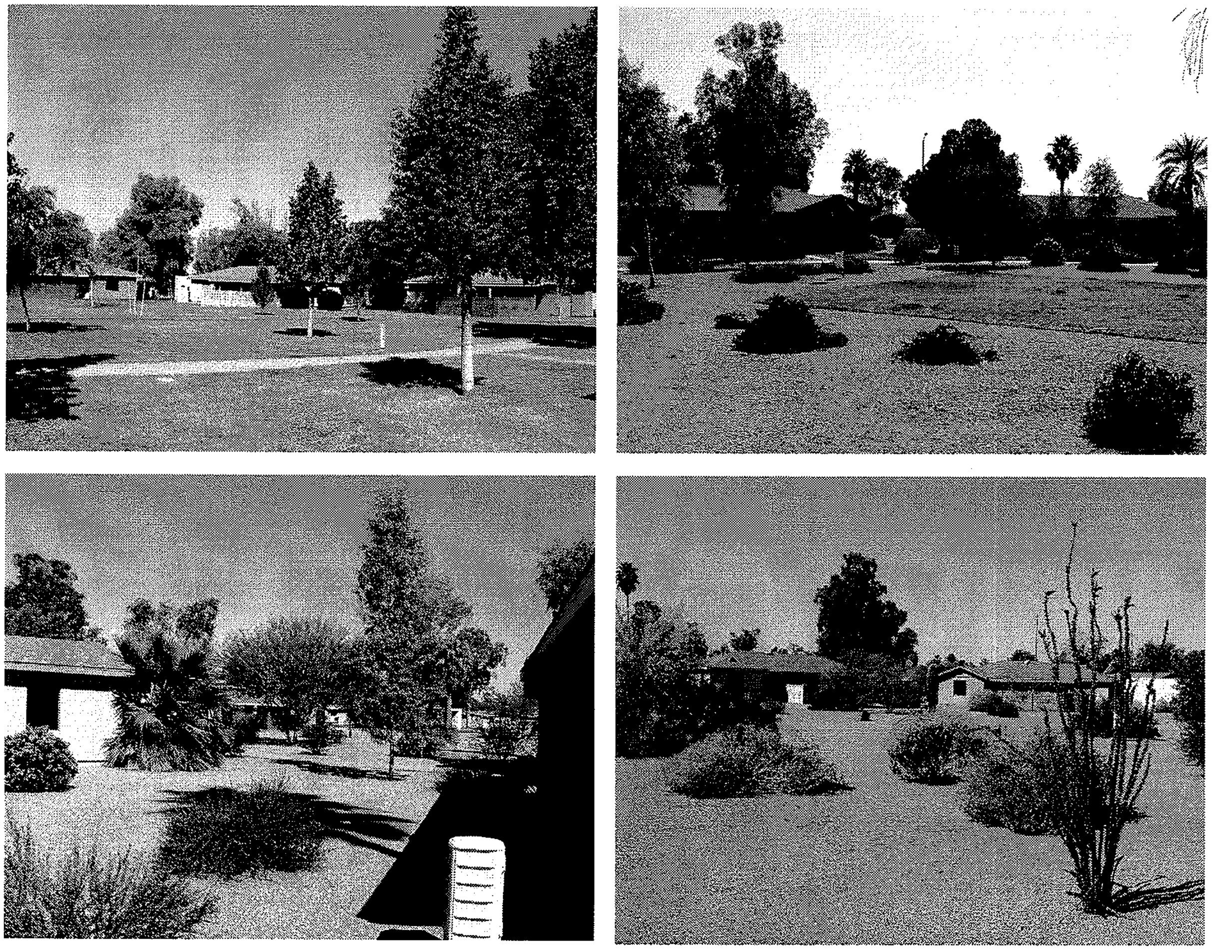

Figure 1. Four North Desert Village residential landscape treatment areas. Images by Chris A. Martin.

Table 2.

List of landscape taxa by scientific^{z} *and common name (in parenthesis) at North Desert Village residential landscape experimental site (Mesa, Arizona). Landscape taxa are distributed by form (T=Tree, S=Shrub, G=Grass) and landscape design treatment (M=Mesic, O=Oasis, X=Xeric, D=Desert).*

Form	Landscape Taxa	NDV Treatment			
		Mesic	Oasis	Xeric	Desert
T	*Acacia salicina* Lindl. (weeping acacia)		O		
T	*Acacia stenophylla* A. Cunn. ex Benth. (shoestring acacia)		O	X	
S	*Bougainvillea spectabilis* Willd. (bougainvillea)		O		
T	*Brachychiton populneus* Schott & Endl. (bottle tree)	M		X	
T	*Brahea armata* S. Watts (Mexican blue fan palm)			X	
S	*Caesalpinia gilliesii* Wallich ex Hook (desert bird-of-paradise)				D
S	*Caesalpinina pulcherrima* L. (Sw.) (red bird-of-paradise)		O		
S	*Calliandra californica* (Benth.) D. Gibs. (red fairy duster)			X	
S	*Carissa grandiflora* E. H. Mey. (natal plum)		O		
P	*Chamaerops humilis* L. (Mediterranean fan palm)		O		
G	Cynodon dactylon (L.) Pers. (bermuda grass)	M	O		
S	*Encelia farinosa* A. Gray (brittle bush)			X	D
T	*Corymbia papuana* (F. Mueller) K.D. Hill and L.A.S. Johnson (ghost gum)		O		
T	*Eucalyptus polyanthemos* Schauer (silver dollar gum)	M			
S	*Justicia californica* (Benth.) D. Gibs. (chuparosa)				D
S	*Lantana hybrid* L. (lantana)		O		
S	*Larrea tridentata* (DC.) Cov. (creosote bush)				D
S	*Leucophyllum frutescens* (Berland.) I.M. Jonst. (Texas sage)	O	X		
S	*Macfadyena unguis cati* (L.) A. Gentry (cat's claw vine)		O		
T	*Melia azaderach* (L.) (Chinaberry)			X	
S	*Myrtus communis* L. (common myrtle)		O		
S	*Nerium oleander* L. (oleander)	M	O	X	D

T	*Olneya tesota* A. Gray. (desert ironwood)				D
T	*Pinus brutia var eldarica* (Ten.) (Afghan pine)	M	O		
T	*Pistacia chinensis* Bunge. (Chinese pistache)	M			
T	*Platycladus orientalis* (L.) Franco (arborvitae)		O		
T	*Parkinsonia hybrid* (hybrid palo verde)			X	
T	*Parkinsonia florida* (Benth. ex Gray) S. Wats (blue palo verde)				D
T	*Platanus wrightii* P. Watts. (Arizona sycamore)	M			
T	*Prosopis alba x chilensis* Grisebach, (Mol.) Stuntz (South American mesquite)			X	
T	*Prosopis velutina* Woot. (velvet mesquite)				D
S	*Ruellia brittoniana* E. Leonard (common ruellia)		O		
S	*Simmondsia chinensis* (Link) C.K. Schneid (jojoba)				D
T	*Ulmus parvifolia* Jacq. (Chinese elm)	M	O		
T	*Washingtonia filifera* (L. Linden) H. Wendl. (desert fan palm)			X	

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[z] Scientific authority found in Hortus Third (1976).

relative humidity, and saturation vapor pressure. An IRR-PN infrared thermometer (Apogee Instruments, Inc., Logan UT) was mounted at 2.0 m height at a 45° angle to measure ground surface temperature (0.0 m). All measurements were processed with a Campbell Scientific 23X datalogger (Campbell Scientific, Logan, UT) and recorded with a digital voice recorder. Because the impact of the urban heat island on humans is most pronounced during periods of intense summer heat, and Arizona experiences monsoon conditions of elevated atmospheric humidity during the late summer, data were recorded during both June (pre-monsoon) and late August to early September (during monsoon) to compare any influences of the summer monsoon on the neighborhood microclimates. Data were recorded during 900-1000, 1600-1700 and 2100-2200 Hr and took about an entire hour to complete; thus, data was collected from only one treatment area per day. Because of this, all four treatments were measured on near-consecutive days with similar synoptic weather conditions of calm, clear days with daily high temperatures within 3°C. Data were recorded again during February (winter) 2008 to provide comparison between the influence of landscape surface cover during winter and summer. Winter collection times were during 900-1000, 1400-1500 and 2000-2100 Hr. For these reasons, data were collected in all four treatment areas on near-consecutive days with similar anticyclonic synoptic weather conditions of clear, calm days.

Five transects were established in each treatment site, radiating from a common centerpoint and extending into the asphalt street. Weather data were

collected starting with the northernmost transect and proceeding in a clockwise direction. Each transect began with the central starting point, and proceeded at 5 m intervals to the surrounding asphalt street.

Observed temperatures (T_{obs}) were adjusted (T_{adj}) before statistical analysis to compensate for changes in synoptic weather conditions during sample periods of data collection. Synoptic weather conditions were derived from shielded copper constantan thermocouples (2 m height) at fixed micro-meteorological stations positioned near the center of each treatment area.

For each of the five days of sampling during each month, the synoptic ambient air temperature ($Tmet_{mean}$) was estimated as the mean of the air temperatures reported by at the four fixed meteorological stations for the morning, afternoon and evening observation intervals as follows:

$$Tmet_{mean} = (Tmet_{mesic}+Tmet_{oasis} + Tmet_{xeric} + Tmet_{desert})/ 4 \qquad \text{Eq. 1}$$

Next, the greater mean ambient air temperature ($Tmet_{Time}$) for mornings, afternoon and evenings across all four days of sampling was estimated as follows:

$$Tmet_{Time} = [Tmet_{mean(Day1)} + Tmet_{mean(Day2)} + Tmet_{mean(Day3)} + Tmet_{mean(Day4)}] / 4 \qquad \text{Eq. 2}$$

$Tmet_{Time}$ gives an estimation of the mean synoptic ambient temperature during mornings, afternoons or evenings across treatments during each monthly sample period. Adjusted temperatures used for statistical analysis of treatment effects on microclimate were then calculated by subtracting the difference between the $Tmet_{mean}$ and the $Tmet_{Time}$ from T_{obs} as follows:

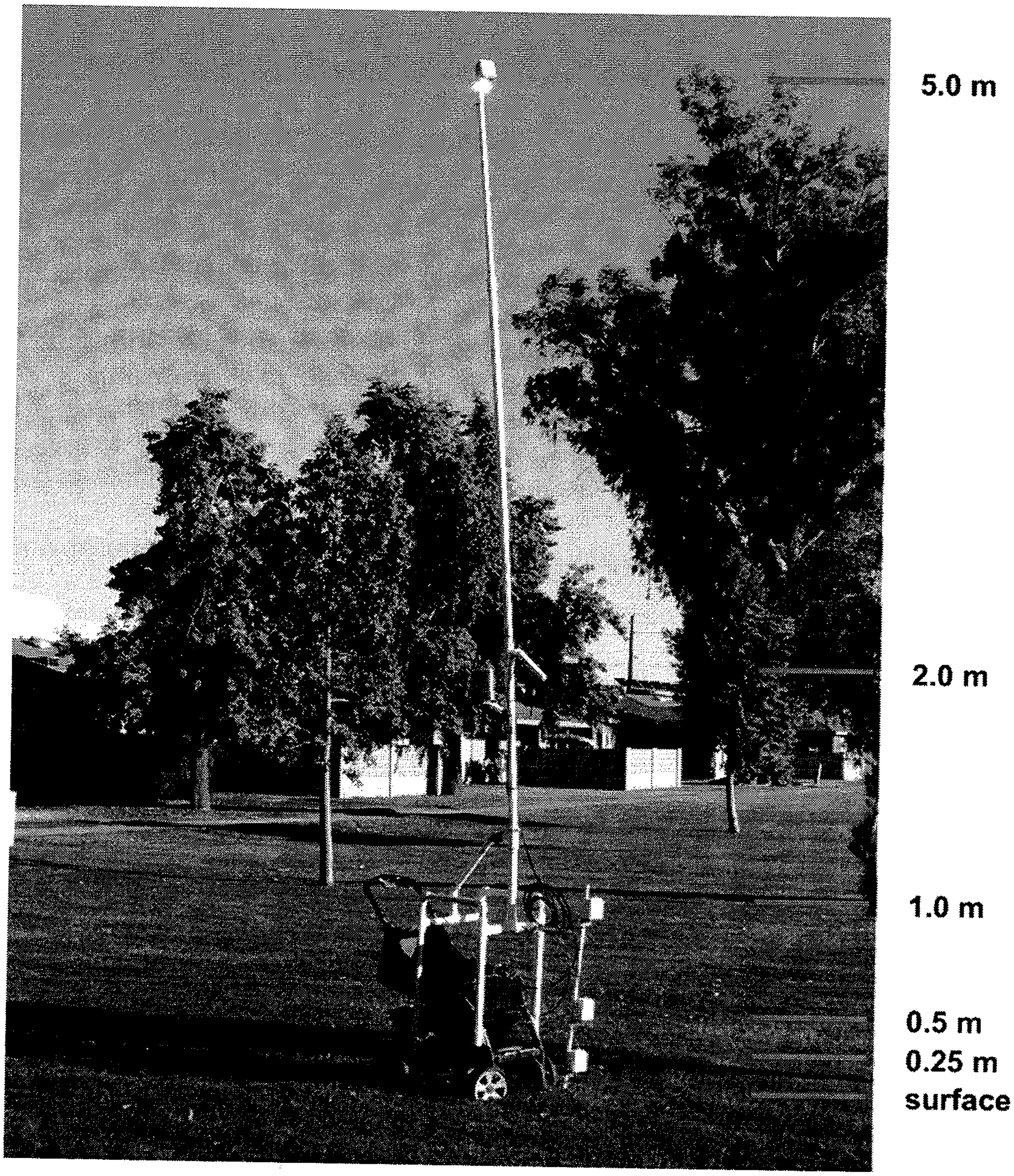


Figure 2. Mobile meteorological station apparatus. Image by Kendra Busse.

$$T_{Adj} = T_{Obs} - (Tmet_{mean} - Tmet_{Time}) \qquad \text{Eq. 3}$$

Thus, T_{adj} is an estimate of T_{obs} for each transect point across treatments had it been possible to measure temperatures for all transect within all the treatments simultaneously for each of the three months.

General linear models procedures were used to test for significance of the variables using a split-plot experimental design (JMP 6.0, Cary, NC). Percent relative humidity and saturation vapor pressure deficit (VPD) data were analyzed by landscape design treatments and time of day within month. Mean values were separated by Tukey's HSD test, alpha =0.5. Temperature data were analyzed by landscape design treatments within month and time of day. For temperature data, regression coefficients were tested for homogeneity of fit using the F-test and Mauchley Criterion Sphericity test. Repeated measures analysis using MANOVA was then used to compare vertical height change profiles in temperature as affected by landscape design treatments. Probabilities for the F-test for height and height times treatment interactions for temperature were made using the Greenhouse-Geiser adjustment to univariate *P* values (Littel, 1989). Two dimensional canonical centroid plots by month and time of day showing adjusted treatment least square means and 95% confidence interval ellipses and bi-plot rays for height were generated to show treatment relationships.

Chapter 3

Results

Overall synoptic weather conditions during the data collection periods were not atypical for the Phoenix area. Table 3 indicates summer 2007 was hot with anticyclonic weather patterns with mean daily high temperatures within 3°C. Winter conditions were cooler with somewhat lower atmospheric pressure. Moreover, synoptic weather conditions were somewhat more variable during winter than during the summer periods. Even with the increased atmospheric variability, mean daily high temperatures in Phoenix were within 7°C.

Throughout the collection period, supplemental irrigation was applied to the mesic, oasis and xeric treatments. Figure 3 shows the monthly irrigation volumes applied to each treatment from April 2007 to April 2008.

Pre-monsoon 2007. Repeated measures analyses of data collected during the morning, afternoon, and evening intervals showed that residential landscape design treatments affected temperature height profiles most extensively in the range of 0 to 2 meters above the landscape surface (Fig. 4a-c). For pre-monsoon mornings, canonical centroid plots and test contrasts between the treatments showed a distinct pairing of desert and xeric treatment temperature height profiles (G-G Epsilon P=0.8161) that were both different from the oasis and mesic profiles (G-G Epsilon P=0.0001) (Fig. 4a). Additionally, the mesic and oasis temperature height profiles were significantly different (G-G Epsilon P=0.0008). The greatest difference in adjusted mean temperatures (13°C) was

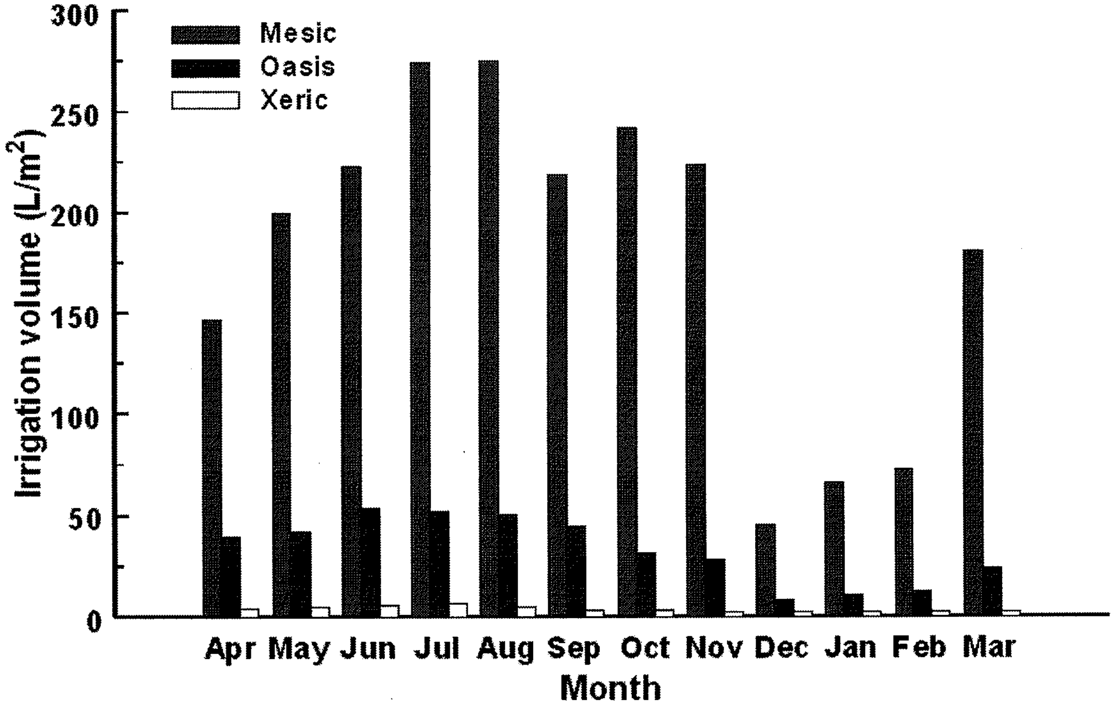
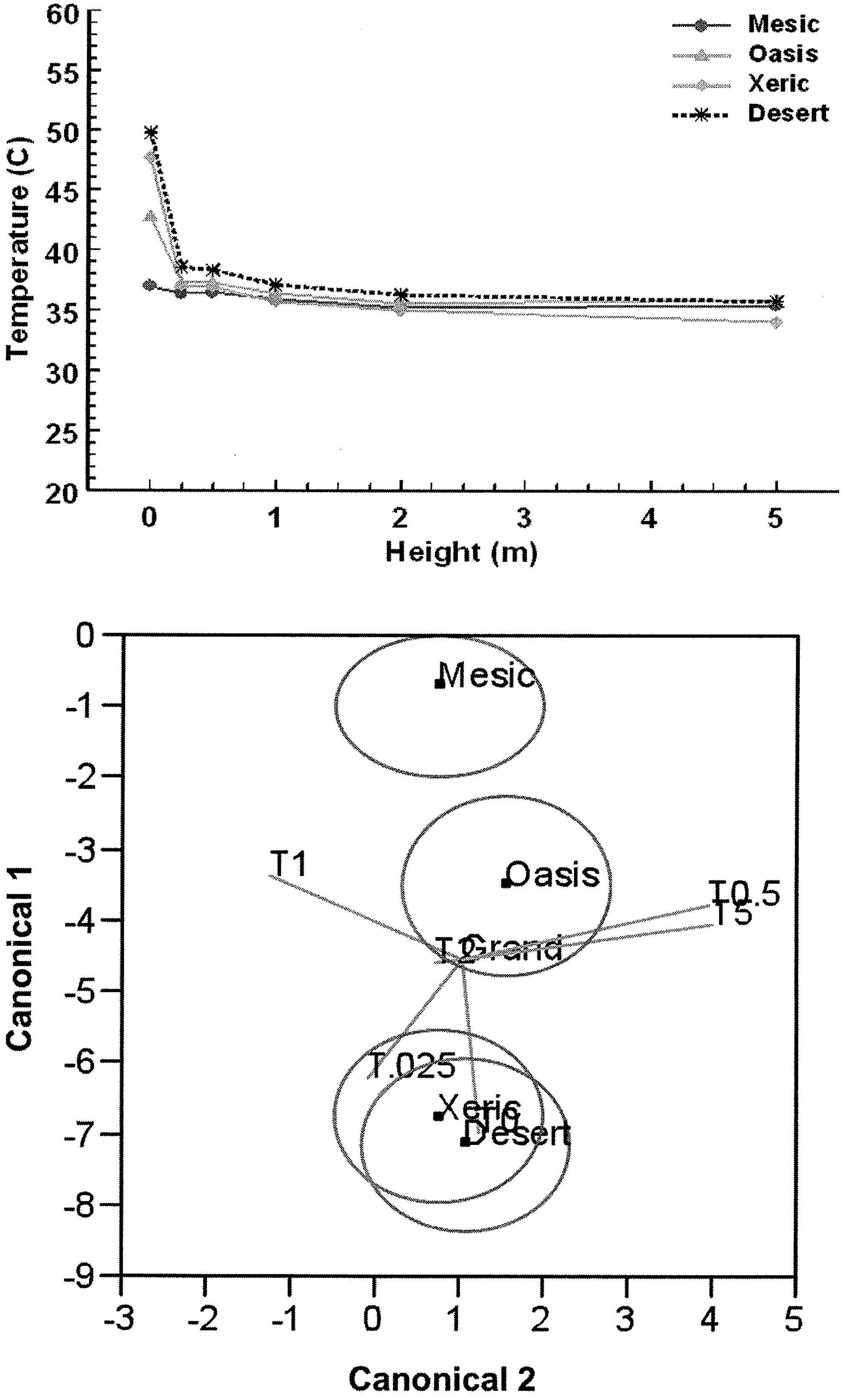


Figure 3. Monthly irrigation volumes applied to landscape design treatments during April 2007 to April 2008. No irrigation was applied to the desert or control treatment areas.

recorded at the landscape surface between the decomposing granite-covered desert (50°C) and turf grass-covered mesic (37°C) treatments. In contrast, treatment-related differences in adjusted mean air temperatures between 0.25 m and 5 m above the surface were 2°C or less. A similarity in the direction of biplot rays within canonical space for height variables during pre-monsoon mornings was detected for the 0.5-m and 5-m heights (Fig. 4a). Across the treatments, morning mean relative humidities and saturation vapor pressures at 2-m height ranged from 11.4% (oasis) to 13.8% (xeric) and 7.13 to 8.19 KPa, respectively (Table 4).

For the pre-monsoon afternoon, canonical centroid plots and test contrasts between the treatments showed a distinct pairing of desert and xeric treatment temperature height profiles (G-G Epsilon P=0.4756) that were both different from the oasis (G-G Epsilon P=0.007) and mesic (G-G Epsilon P=0.0001) temperature height profiles (Fig. 4b). Additionally, the mesic and oasis temperature height profiles were significantly different (G-G Epsilon P=0.0001). Similar to the pre-monsoon morning data, the greatest difference in adjusted mean temperature (22°C) during pre-monsoon afternoons was recorded at the landscape surface between the desert (55°C) and mesic (33°C) treatments. The treatment-related differences in adjusted mean temperatures between 0.025 m and 5 m ranged from approximately 4°C to less than 2°C. For pre-monsoon afternoons, a similarity in the direction in canonical space of biplot rays for height variables was detected for the surface and 0.5-m heights (Fig. 4b). Across

Figure 4a.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Height (m)
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Figure 4a. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during premonsoon 2007 morning (900 to 1000 Hr) in response to four landscape design treatments. Treatments include: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

Below: Canonical correlation analysis. Canonical circles show the 95% confidence intervals around the distribution centroid of each landscape design treatment. Overlapping centriods indicate that those treatments are not significantly different from each other. Biplot rays, originating from the grand mean show directions of relative responsiveness in canonical space. (T0=surface, T.025=0.25 m, T.05=0.5 m, T1=1.0 m, T2=2.0 m, T5=5.0 m).

Table 3.

Synoptic weather conditions during data collection periods. The temperature (°C) is given for the 30-year average and average during data collection. Average relative humidity, shown as a percentage, (RH) and geopotential height (GPH) are given for the data collection period.

Collection Period	Average Temperature (°C) 30 Year	 Period	Avg RH (%)	GPH
Pre-monsoon	39.2	39.6	14.4	5890
Monsoon	40.6	40.9	32.0	5870
Winter	21.8	19.7	68.5	5710

Table 4.

Mean percent relative humidity (RH) and saturation vapor pressure (Sat VP) at 2 m during morning, afternoon and evening collection periods pre-monsoon and monsoon 2007 and winter 2008.

Month Treatment	Morning		Afternoon		Evening	
	RH (%)	Sat VP (kPa)	RH (%)	Sat VP (kPa)	RH (%)	Sat VP (kPa)
Pre-monsoon						
Mesic	13.2 b	7.13 d	10.7 a	7.39 c	21.9 a	4.35 b
Oasis	11.4 c	8.19 a	8.6 c	7.68 b	15.9 c	4.58 a
Xeric	13.8 a	7.33 c	9.2 b	7.95 a	17.4 b	4.59 a
Desert	11.7 c	7.79 b	8.3 c	7.83 ab	13.7 d	4.40 b
Monsoon						
Mesic	28.6 c	5.32 b	18.9 b	7.13 d	24.3 d	4.40 d
Oasis	30.9 b	5.83 a	14.6 d	8.19 a	25.2 c	5.50 a
Xeric	31.2 b	5.37 b	16.8 c	7.33 c	35.8 b	4.65 c
Desert	34.7 a	5.89 a	22.0 a	7.79 b	44.9 a	4.74 b
Winter						
Mesic	59.9 c	1.48 a	31.5 c	2.70 a	61.6 b	1.64 b
Oasis	66.3 b	1.38 b	25.3 d	2.62 b	41.8 c	1.74 a
Xeric	70.6 a	1.14 c	35.2 a	2.14 c	70.1 a	1.31 c
Desert	65.7 b	1.05 d	32.9 b	1.78 d	67.8 a	1.22 d

Values are treatment means, n=40. Treatment means in columns by month followed by the same letter are not significantly different, Tukey's HSD test alpha = 0.05.

all four treatments, mean relative humidity and saturation vapor pressures ranged from 8.3% (desert) to 10.7% (mesic) and 7.39 to 7.95 KPa, respectively (Table 4).

Unlike the pre-monsoon morning or afternoon temperature height profiles, the pre-monsoon evening temperature height profiles for all treatments were generally coolest at the landscape surface (Fig. 4c). Canonical centroid plots and test contrasts between the treatments showed a marginally significant pairing of desert and xeric treatment temperature height profiles (G-G Epsilon P=0.0588) that were both different from the oasis profile (G-G Epsilon P=0.0009) and mesic profiles (G-G Epsilon P=0.0001). Additionally, the mesic and oasis temperature height profiles were significantly different (G-G Epsilon P=0.0001). The greatest difference in adjusted mean temperatures (9°C) during the evening was recorded at the landscape surface between the decomposing granite covered xeric (28°C) and turf grass covered mesic (19°C) treatments. Similar to afternoon air temperatures, treatment-related differences in adjusted mean air temperatures above the surface ranged from 4°C at the 0.025-m height to less than 2°C at the 2-m and 5-m heights. The directions of biplot rays in canonical space for all height variables during the pre-monsoon evening were different (Fig. 4c). Mean relative humidity and saturation vapor pressures across all treatments during the pre-monsoon evening interval ranged from 13.7% (desert) to 21.9% (mesic) and 4.35 to 4.59 KPa, respectively (Table 4).

Figure 4b.

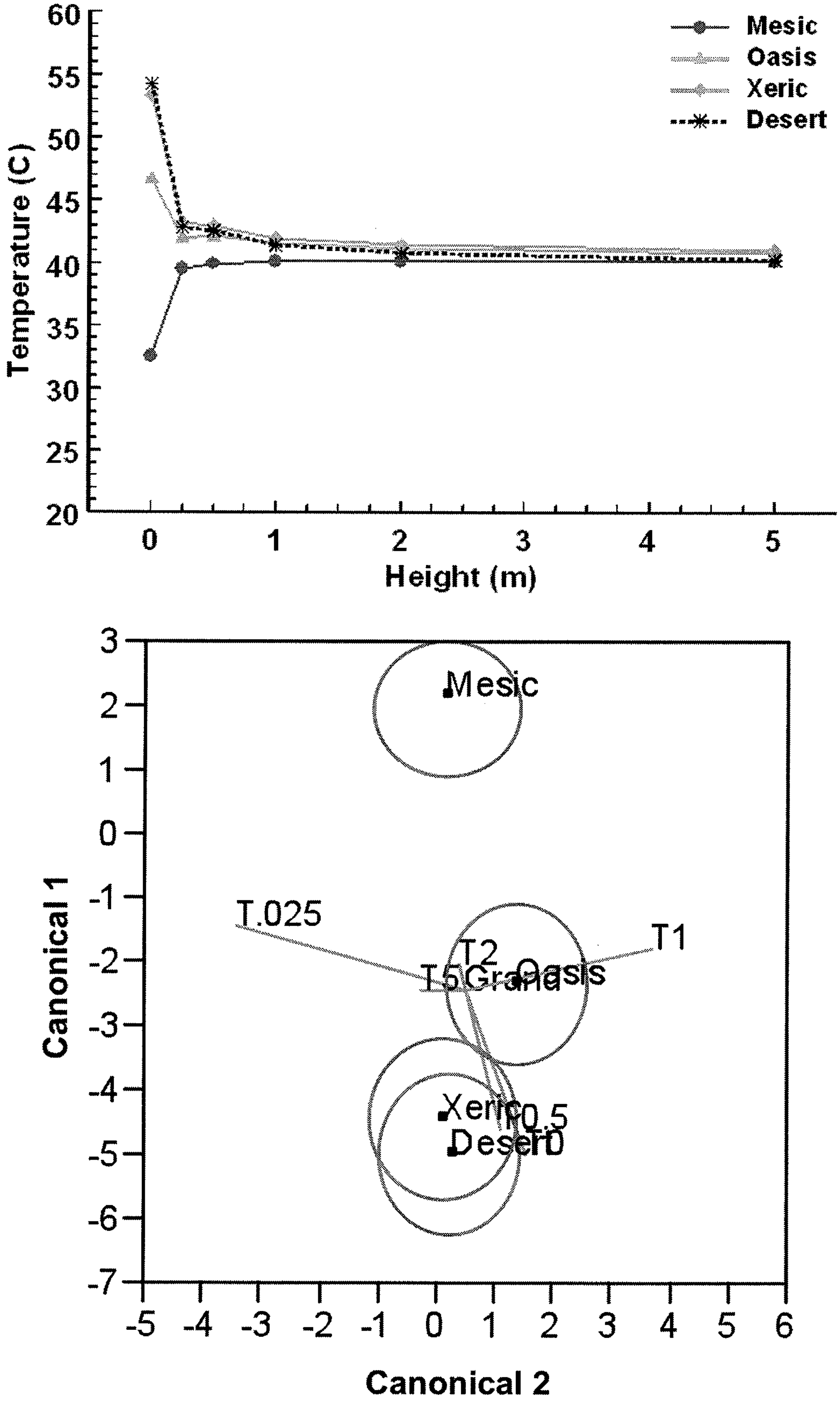
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Figure 4b. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during premonsoon 2007 afternoon (1600 to 1700 Hr) in response to four landscape design treatments. Treatments include: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

Below: Canonical correlation analysis. Canonical circles show the 95% confidence intervals around the distribution centroid of each landscape design treatment. Overlapping centriods indicate that those treatments are not significantly different from each other. Biplot rays, originating from the grand mean show directions of relative responsiveness in canonical space. (T0=surface, T.025=0.25 m, T.05=0.5 m, T1=1.0 m, T2=2.0 m, T5=5.0 m).

Figure 4c.

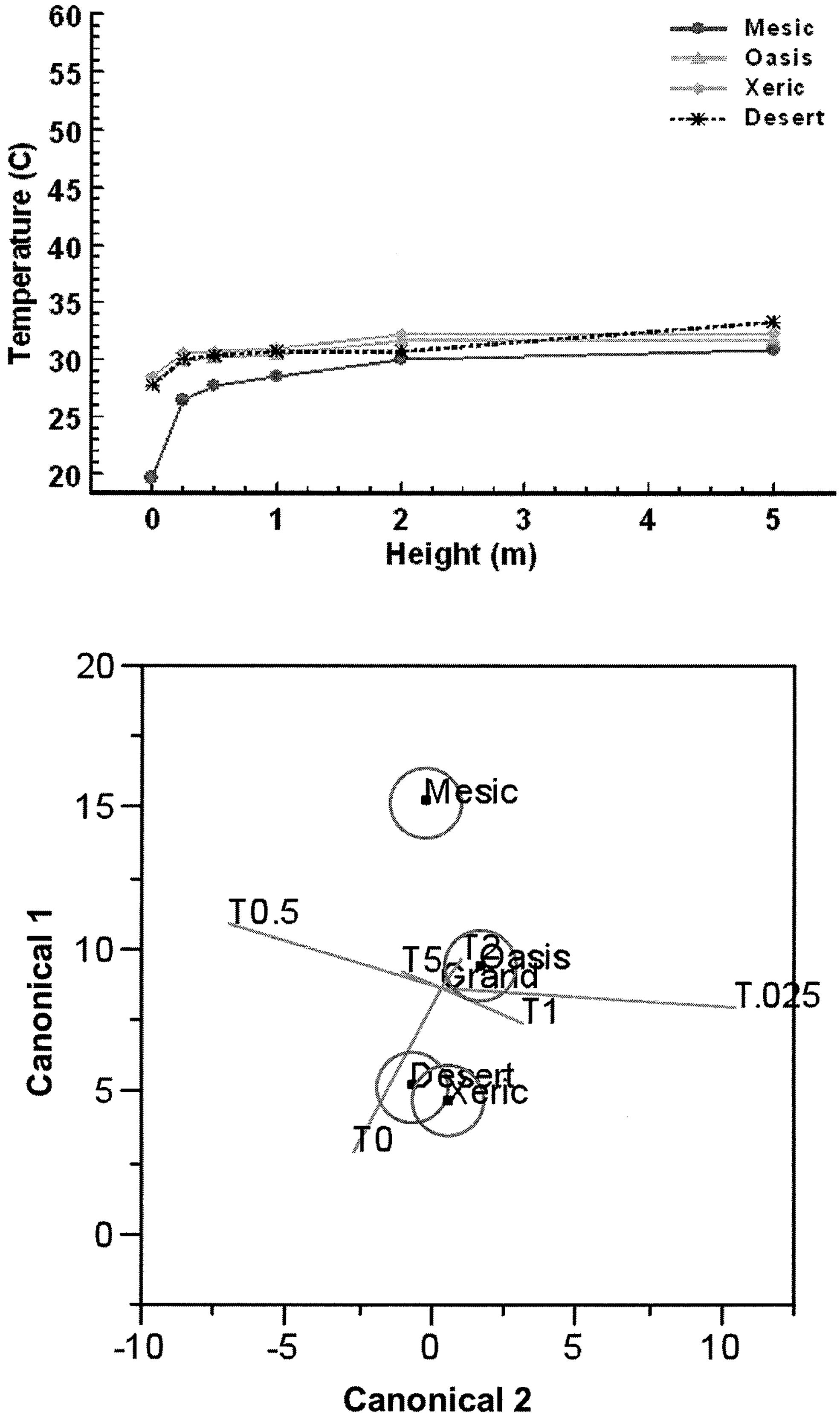
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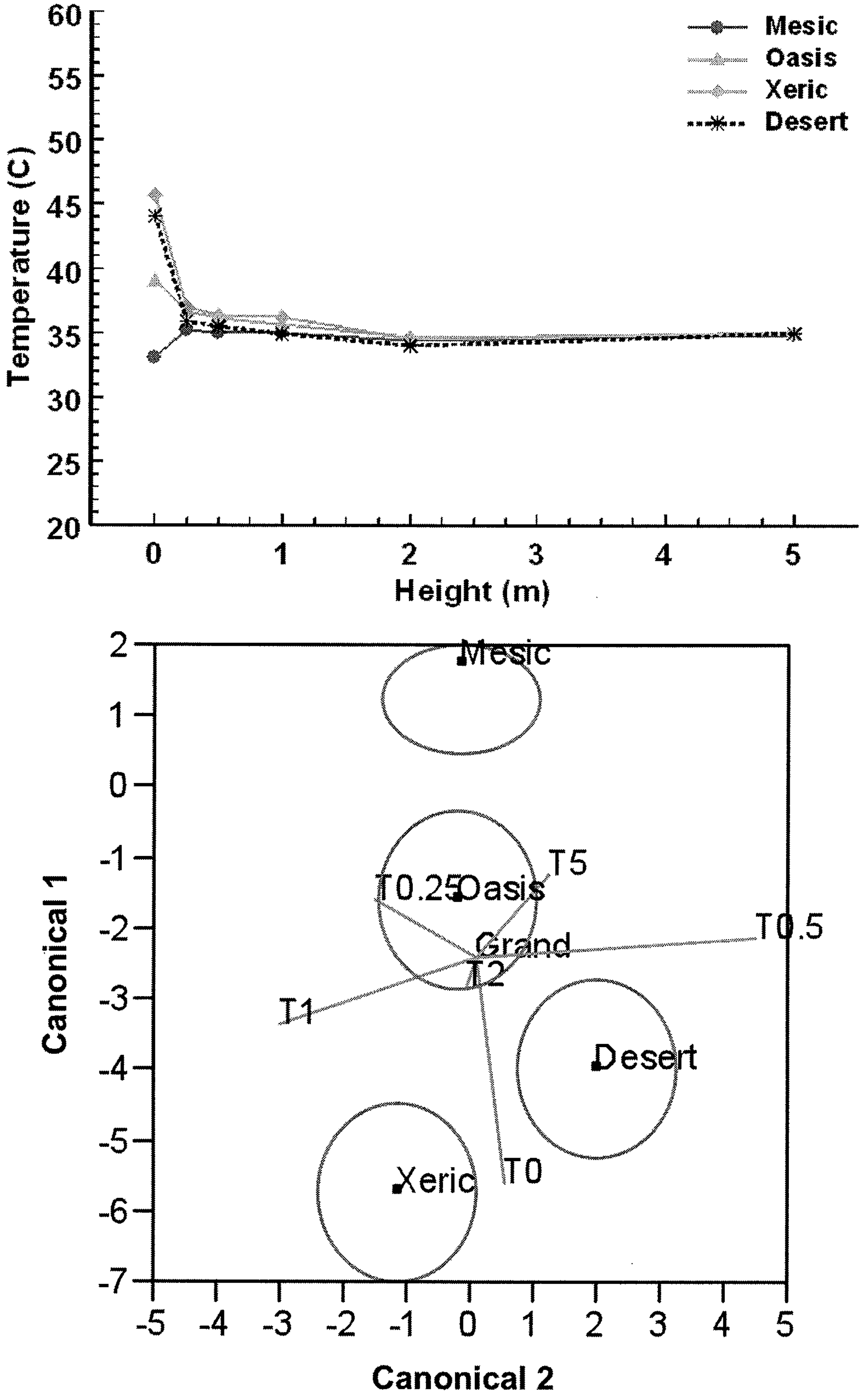
Figure 4c. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during premonsoon 2007 evening (2100 to 2200 Hr) in response to four landscape design treatments. Treatments were: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

Below: Canonical correlation analysis. Canonical circles show the 95% confidence intervals around the distribution centroid of each landscape design treatment. Overlapping centriods indicate that those treatments are not significantly different from each other. Biplot rays, originating from the grand mean show directions of relative responsiveness in canonical space. (T0=surface, T.025=0.25 m, T.05=0.5 m, T1=1.0 m, T2=2.0 m, T5=5.0 m).

Monsoon 2007. Repeated measures analyses of data collected during the morning, afternoon, and evening intervals showed that residential landscape design treatments affected temperature height profiles most extensively in the range of 0 to 2 meters above the landscape surface (Fig. 5a-c). For the monsoon morning interval, canonical centroid plots and test contrasts between the treatments revealed a distinct pairing of desert and xeric treatment temperature height profiles (G-G Epsilon P=0.4162) that were both different from the oasis and mesic profiles (G-G Epsilon P=0.0001) (Fig. 5a). Additionally, the mesic and oasis temperature height profiles were significantly different (G-G Epsilon P=0.0001). The greatest difference in adjusted mean temperatures (13°C) during the evening was recorded at the landscape surface between the decomposing granite-covered xeric (46°C) and turf grass-covered mesic (33°C) treatments. In contrast, treatment-related differences in adjusted mean air temperatures between the 0.25-m and 5-m heights were 2°C or less. The directions within canonical space of biplot rays for all height variables during the pre-monsoon morning were different (Fig. 5a). Mean relative humidities and saturation vapor pressures across treatments during this morning interval ranged from 28.6% (mesic) to 34.7% (desert) and 5.32 to 5.89 KPa, respectively (Table 4).

For the monsoon afternoon, canonical centroid plots and test contrasts between the treatments showed a distinct pairing of desert and xeric treatment temperature height profiles (G-G Epsilon P=0.2186) that were both different from the oasis (G-G Epsilon P=0.0003) and mesic (G-G Epsilon P=0.0001) temperature height profiles. Additionally, the mesic and oasis temperature height

Figure 5a.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Desert
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Canonical 2

Figure 5a. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during monsoon 2007 morning (900 to 1000 Hr) in response to four landscape design treatments. Treatments include: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

Below: Canonical correlation analysis. Canonical circles show the 95% confidence intervals around the distribution centroid of each landscape design treatment. Overlapping centriods indicate that those treatments are not significantly different from each other. Biplot rays, originating from the grand mean show directions of relative responsiveness in canonical space. (T0=surface, T.025=0.25 m, T.05=0.5 m, T1=1.0 m, T2=2.0 m, T5=5.0 m).

profiles were significantly different (G-G Epsilon P=0.0035). The greatest difference in adjusted mean temperatures during the afternoon was at the landscape surface (18°C) and was recorded between the desert (53°C) and mesic (35°C) treatments. Treatment-related differences in adjusted mean temperatures were 2°C or less between 2-m and 5-m heights. For monsoon afternoon, similarities in the direction of biplot rays within canonical space for height variables were detected for the surface and 0.5-m height (Fig. 5b). Mean relative humidities and saturation vapor pressures across treatments during this morning interval ranged from 14.6% (oasis) to 22.0% (desert) and 7.13 to 8.19 KPa, respectively (Table 4).

For monsoon evening, the temperature profile of the unirrigated, decomposing granite-covered desert landscape treatment showed a virtually constant adjusted air temperature (ca. 32°C) from the surface to 5.0 m height (Fig. 5c). Otherwise, the temperature height profiles of the other treatments exhibited various trends toward decreased temperatures at the surface that were related to the extent of turf grass cover (Fig. 5c). Canonical centroid plots and test contrasts between the treatments showed that the temperature height profiles of each treatment were different from one another (G-G Epsilon P=0.0001). The greatest difference in adjusted mean temperatures was at the landscape surface (13°C) and was recorded between the desert (34°C) and mesic (21°C) treatments. Just like the adjusted air temperatures during the monsoon afternoons, treatment-related differences in adjusted mean temperatures were 2°C or less between 1 m and 5 m (Fig. 5c). For monsoon evenings, a strong dissimilarity within canonical space in the direction of biplot rays for height variables was

Figure 5b.

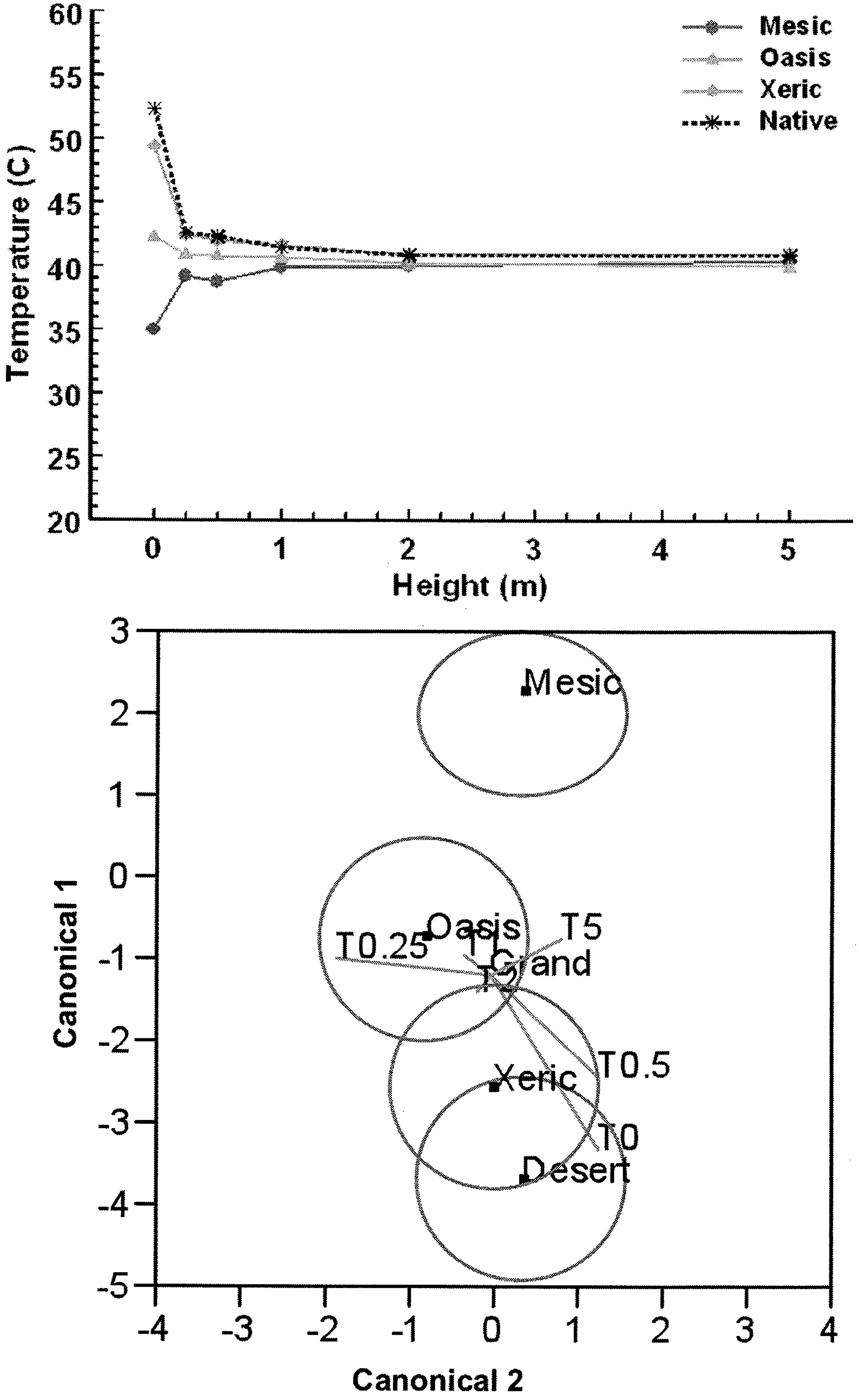
Mesic
Oasis
Xeric
Native
Temperature (C)
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Figure 5b. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during monsoon 2007 afternoon (1600 to 1700 Hr) in response to four landscape design treatments. Treatments include: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

Below: Canonical correlation analysis. Canonical circles show the 95% confidence intervals around the distribution centroid of each landscape design treatment. Overlapping centriods indicate that those treatments are not significantly different from each other. Biplot rays, originating from the grand mean show directions of relative responsiveness in canonical space. (T0=surface, T.025=0.25 m, T.05=0.5 m, T1=1.0 m, T2=2.0 m, T5=5.0 m).

Figure 4a. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during premonsoon 2007 morning (900 to 1000 Hr) in response to four landscape design treatments. Treatments include: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

Below: Canonical correlation analysis. Canonical circles show the 95% confidence intervals around the distribution centroid of each landscape design treatment. Overlapping centriods indicate that those treatments are not significantly different from each other. Biplot rays, originating from the grand mean show directions of relative responsiveness in canonical space. (T0=surface, T.025=0.25 m, T.05=0.5 m, T1=1.0 m, T2=2.0 m, T5=5.0 m).

Table 3.

Synoptic weather conditions during data collection periods. The temperature (°C) is given for the 30-year average and average during data collection. Average relative humidity, shown as a percentage, (RH) and geopotential height (GPH) are given for the data collection period.

Collection Period	Average Temperature (°C) 30 Year	Period	Avg RH (%)	GPH
Pre-monsoon	39.2	39.6	14.4	5890
Monsoon	40.6	40.9	32.0	5870
Winter	21.8	19.7	68.5	5710

Table 4.

Mean percent relative humidity (RH) and saturation vapor pressure (Sat VP) at 2 m during morning, afternoon and evening collection periods pre-monsoon and monsoon 2007 and winter 2008.

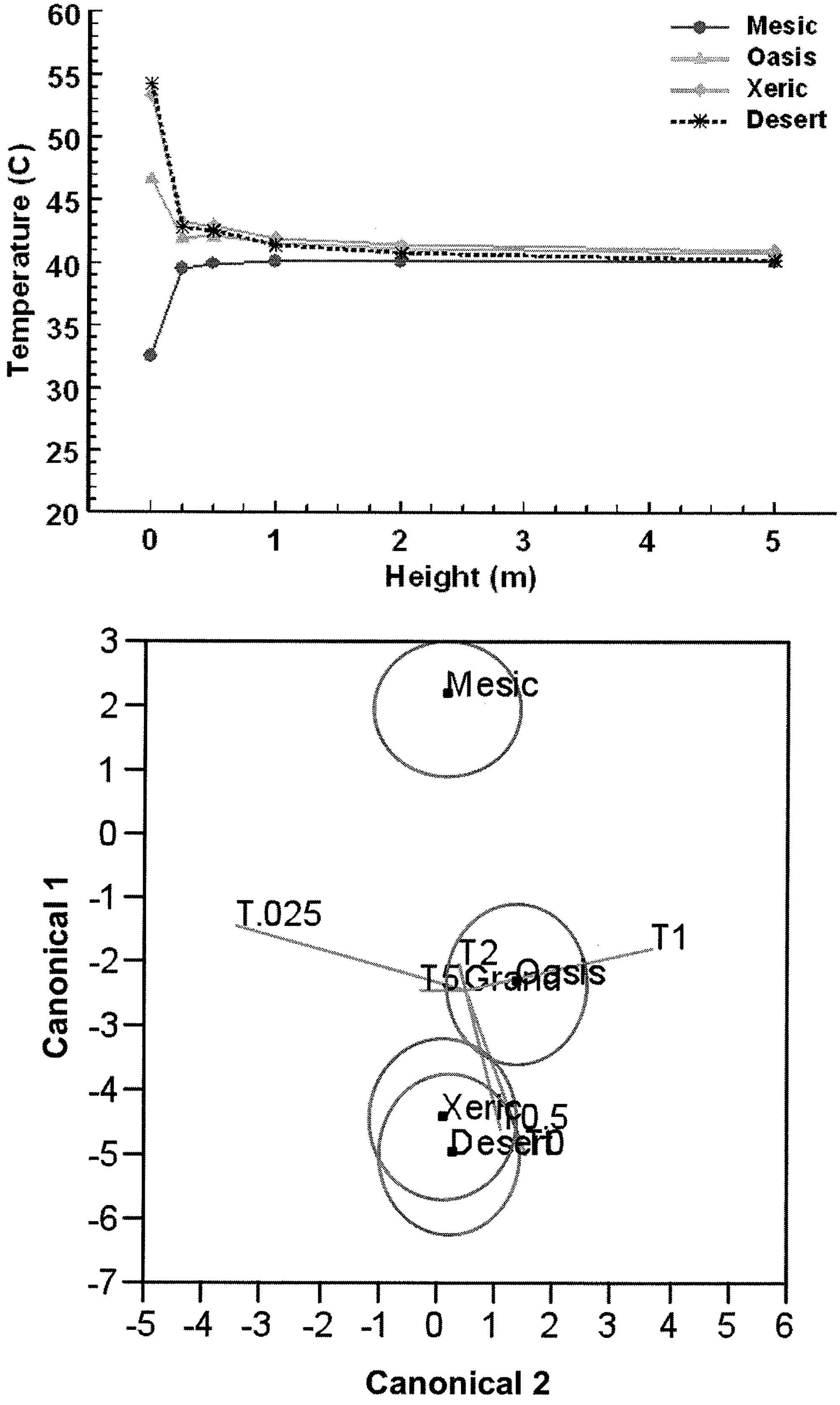
Month Treatment	Morning		Afternoon		Evening	
	RH (%)	Sat VP (kPa)	RH (%)	Sat VP (kPa)	RH (%)	Sat VP (kPa)
Pre-monsoon						
Mesic	13.2 b	7.13 d	10.7 a	7.39 c	21.9 a	4.35 b
Oasis	11.4 c	8.19 a	8.6 c	7.68 b	15.9 c	4.58 a
Xeric	13.8 a	7.33 c	9.2 b	7.95 a	17.4 b	4.59 a
Desert	11.7 c	7.79 b	8.3 c	7.83 ab	13.7 d	4.40 b
Monsoon						
Mesic	28.6 c	5.32 b	18.9 b	7.13 d	24.3 d	4.40 d
Oasis	30.9 b	5.83 a	14.6 d	8.19 a	25.2 c	5.50 a
Xeric	31.2 b	5.37 b	16.8 c	7.33 c	35.8 b	4.65 c
Desert	34.7 a	5.89 a	22.0 a	7.79 b	44.9 a	4.74 b
Winter						
Mesic	59.9 c	1.48 a	31.5 c	2.70 a	61.6 b	1.64 b
Oasis	66.3 b	1.38 b	25.3 d	2.62 b	41.8 c	1.74 a
Xeric	70.6 a	1.14 c	35.2 a	2.14 c	70.1 a	1.31 c
Desert	65.7 b	1.05 d	32.9 b	1.78 d	67.8 a	1.22 d

Values are treatment means, n=40. Treatment means in columns by month followed by the same letter are not significantly different, Tukey's HSD test alpha = 0.05.

all four treatments, mean relative humidity and saturation vapor pressures ranged from 8.3% (desert) to 10.7% (mesic) and 7.39 to 7.95 KPa, respectively (Table 4).

Unlike the pre-monsoon morning or afternoon temperature height profiles, the pre-monsoon evening temperature height profiles for all treatments were generally coolest at the landscape surface (Fig. 4c). Canonical centroid plots and test contrasts between the treatments showed a marginally significant pairing of desert and xeric treatment temperature height profiles (G-G Epsilon P=0.0588) that were both different from the oasis profile (G-G Epsilon P=0.0009) and mesic profiles (G-G Epsilon P=0.0001). Additionally, the mesic and oasis temperature height profiles were significantly different (G-G Epsilon P=0.0001). The greatest difference in adjusted mean temperatures (9°C) during the evening was recorded at the landscape surface between the decomposing granite covered xeric (28°C) and turf grass covered mesic (19°C) treatments. Similar to afternoon air temperatures, treatment-related differences in adjusted mean air temperatures above the surface ranged from 4°C at the 0.025-m height to less than 2°C at the 2-m and 5-m heights. The directions of biplot rays in canonical space for all height variables during the pre-monsoon evening were different (Fig. 4c). Mean relative humidity and saturation vapor pressures across all treatments during the pre-monsoon evening interval ranged from 13.7% (desert) to 21.9% (mesic) and 4.35 to 4.59 KPa, respectively (Table 4).

Figure 4b.


Temperature (C)
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Height (m)
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Oasis
Xeric
Desert
Canonical 1
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-6
-7
Canonical 2
-5
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-2
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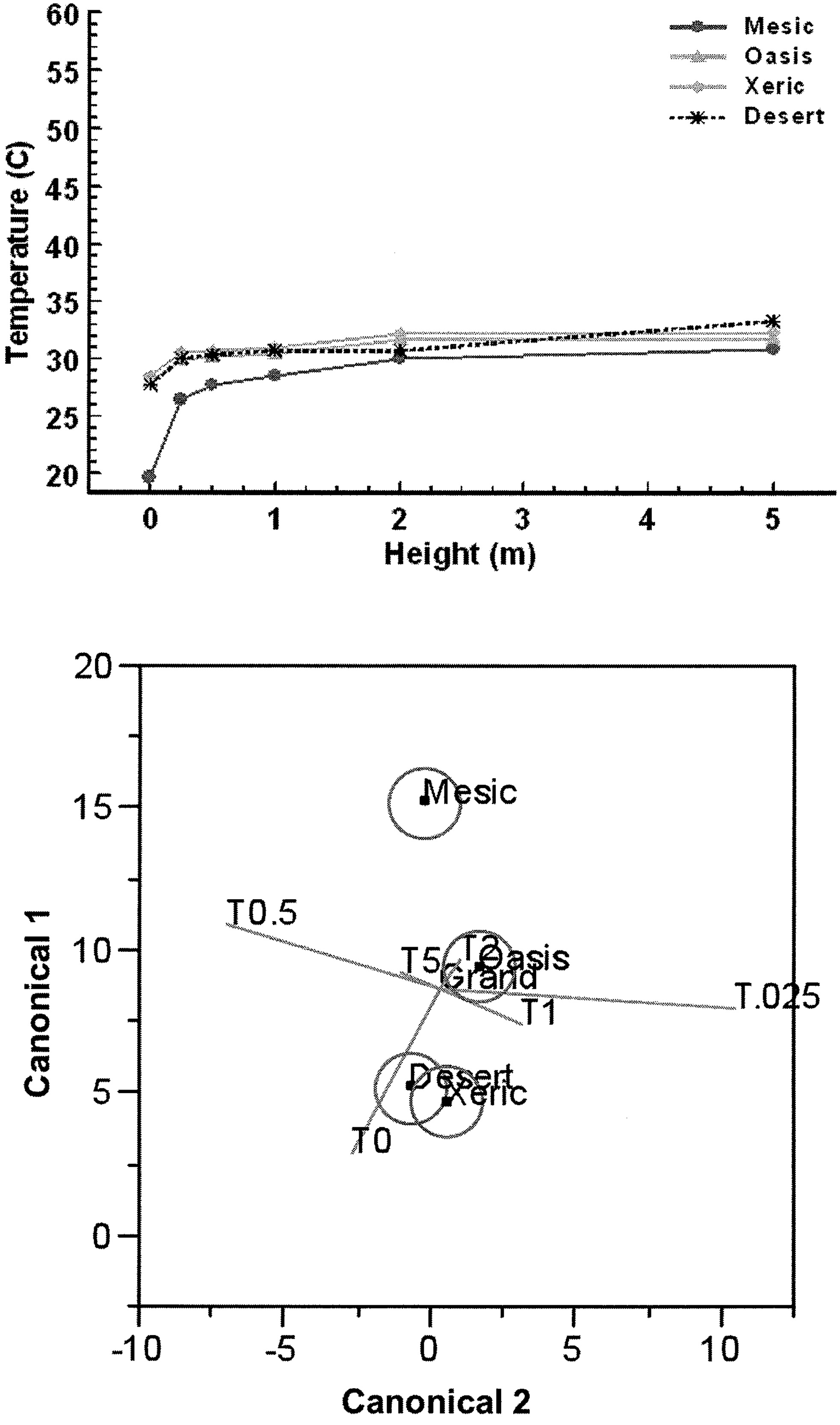
3
4
5
6
Mesic
T.025
T1
T2
T5
Grand
Oasis
Xeric
T0.5
Desert
T0

Figure 4b. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during premonsoon 2007 afternoon (1600 to 1700 Hr) in response to four landscape design treatments. Treatments include: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

Below: Canonical correlation analysis. Canonical circles show the 95% confidence intervals around the distribution centroid of each landscape design treatment. Overlapping centriods indicate that those treatments are not significantly different from each other. Biplot rays, originating from the grand mean show directions of relative responsiveness in canonical space. (T0=surface, T.025=0.25 m, T.05=0.5 m, T1=1.0 m, T2=2.0 m, T5=5.0 m).

Figure 4c.


Mesic
Oasis
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Desert
Temperature (C)
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Canonical 1
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Canonical 2
Mesic
T0.5
T5
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Oasis
Grand
T1
T.025
Desert
Xeric
T0

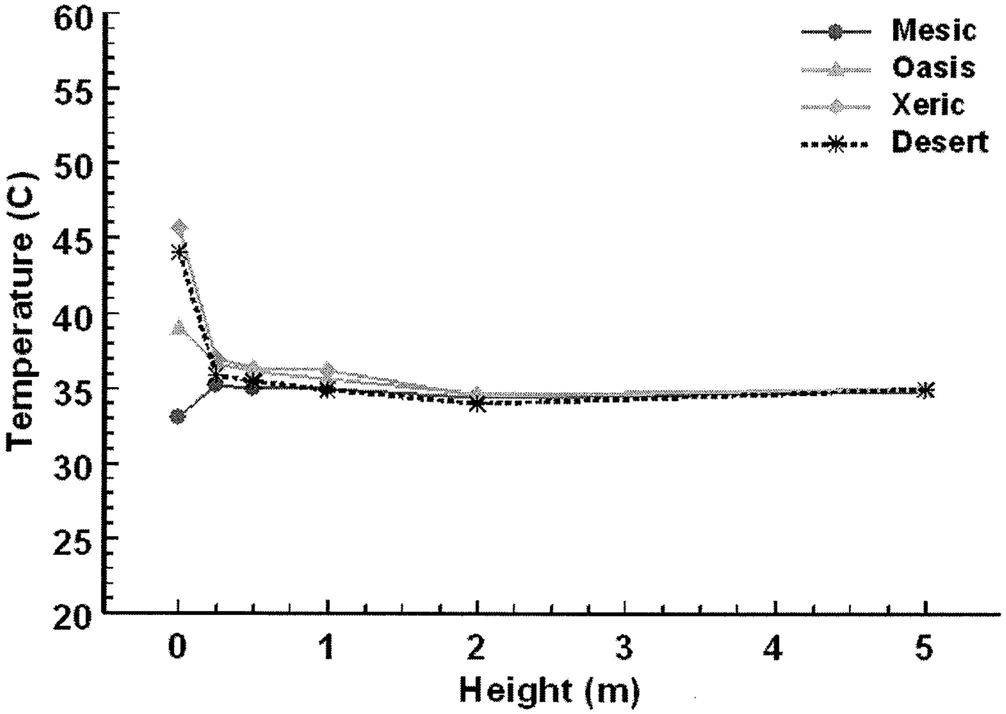
Figure 4c. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during premonsoon 2007 evening (2100 to 2200 Hr) in response to four landscape design treatments. Treatments were: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

Below: Canonical correlation analysis. Canonical circles show the 95% confidence intervals around the distribution centroid of each landscape design treatment. Overlapping centriods indicate that those treatments are not significantly different from each other. Biplot rays, originating from the grand mean show directions of relative responsiveness in canonical space. (T0=surface, T.025=0.25 m, T.05=0.5 m, T1=1.0 m, T2=2.0 m, T5=5.0 m).

Monsoon 2007. Repeated measures analyses of data collected during the morning, afternoon, and evening intervals showed that residential landscape design treatments affected temperature height profiles most extensively in the range of 0 to 2 meters above the landscape surface (Fig. 5a-c). For the monsoon morning interval, canonical centroid plots and test contrasts between the treatments revealed a distinct pairing of desert and xeric treatment temperature height profiles (G-G Epsilon P=0.4162) that were both different from the oasis and mesic profiles (G-G Epsilon P=0.0001) (Fig. 5a). Additionally, the mesic and oasis temperature height profiles were significantly different (G-G Epsilon P=0.0001). The greatest difference in adjusted mean temperatures (13°C) during the evening was recorded at the landscape surface between the decomposing granite-covered xeric (46°C) and turf grass-covered mesic (33°C) treatments. In contrast, treatment-related differences in adjusted mean air temperatures between the 0.25-m and 5-m heights were 2°C or less. The directions within canonical space of biplot rays for all height variables during the pre-monsoon morning were different (Fig. 5a). Mean relative humidities and saturation vapor pressures across treatments during this morning interval ranged from 28.6% (mesic) to 34.7% (desert) and 5.32 to 5.89 KPa, respectively (Table 4).

For the monsoon afternoon, canonical centroid plots and test contrasts between the treatments showed a distinct pairing of desert and xeric treatment temperature height profiles (G-G Epsilon P=0.2186) that were both different from the oasis (G-G Epsilon P=0.0003) and mesic (G-G Epsilon P=0.0001) temperature height profiles. Additionally, the mesic and oasis temperature height

Figure 5a.


Mesic
Oasis
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Desert
Temperature (C)
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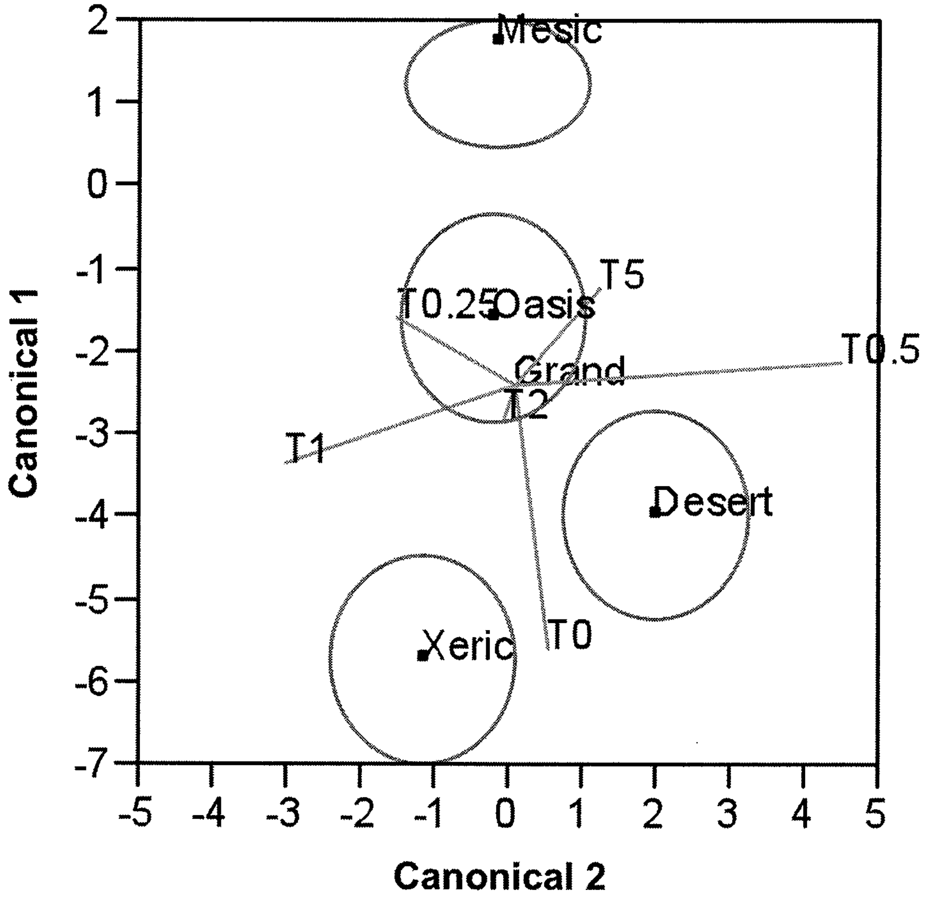
Height (m)


Mesic
Oasis
T0.25
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Desert
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Canonical 1
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Canonical 2

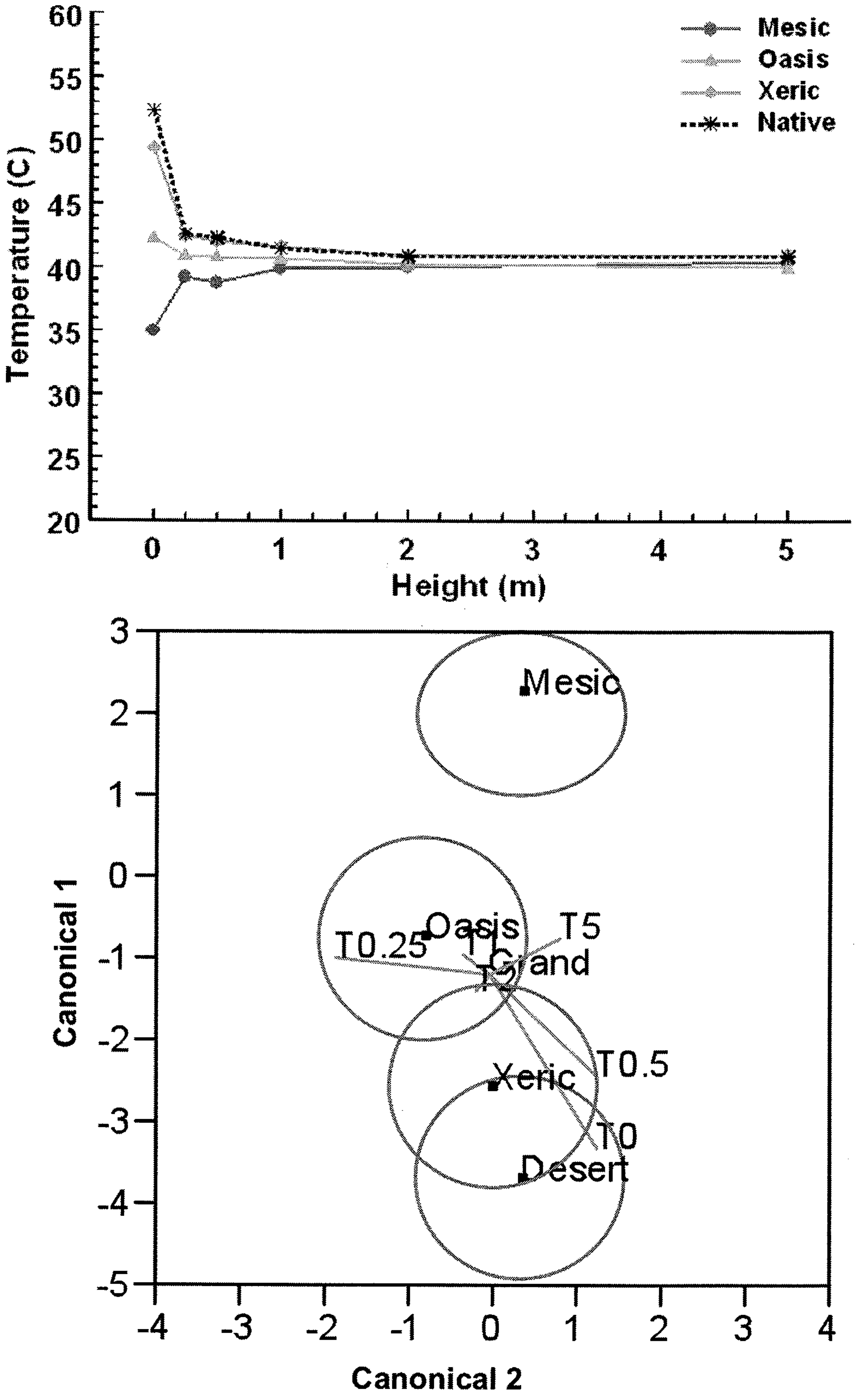
Figure 5a. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during monsoon 2007 morning (900 to 1000 Hr) in response to four landscape design treatments. Treatments include: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

Below: Canonical correlation analysis. Canonical circles show the 95% confidence intervals around the distribution centroid of each landscape design treatment. Overlapping centriods indicate that those treatments are not significantly different from each other. Biplot rays, originating from the grand mean show directions of relative responsiveness in canonical space. (T0=surface, T.025=0.25 m, T.05=0.5 m, T1=1.0 m, T2=2.0 m, T5=5.0 m).

profiles were significantly different (G-G Epsilon P=0.0035). The greatest difference in adjusted mean temperatures during the afternoon was at the landscape surface (18°C) and was recorded between the desert (53°C) and mesic (35°C) treatments. Treatment-related differences in adjusted mean temperatures were 2°C or less between 2-m and 5-m heights. For monsoon afternoon, similarities in the direction of biplot rays within canonical space for height variables were detected for the surface and 0.5-m height (Fig. 5b). Mean relative humidities and saturation vapor pressures across treatments during this morning interval ranged from 14.6% (oasis) to 22.0% (desert) and 7.13 to 8.19 KPa, respectively (Table 4).

For monsoon evening, the temperature profile of the unirrigated, decomposing granite-covered desert landscape treatment showed a virtually constant adjusted air temperature (ca. 32°C) from the surface to 5.0 m height (Fig. 5c). Otherwise, the temperature height profiles of the other treatments exhibited various trends toward decreased temperatures at the surface that were related to the extent of turf grass cover (Fig. 5c). Canonical centroid plots and test contrasts between the treatments showed that the temperature height profiles of each treatment were different from one another (G-G Epsilon P=0.0001). The greatest difference in adjusted mean temperatures was at the landscape surface (13°C) and was recorded between the desert (34°C) and mesic (21°C) treatments. Just like the adjusted air temperatures during the monsoon afternoons, treatment-related differences in adjusted mean temperatures were 2°C or less between 1 m and 5 m (Fig. 5c). For monsoon evenings, a strong dissimilarity within canonical space in the direction of biplot rays for height variables was

Figure 5b.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Height (m)
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Canonical 2
Mesic
Oasis
T0.25
T1
T5
Grand
T2
T0.5
Xeric
T0
Desert

Figure 5b. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during monsoon 2007 afternoon (1600 to 1700 Hr) in response to four landscape design treatments. Treatments include: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

Below: Canonical correlation analysis. Canonical circles show the 95% confidence intervals around the distribution centroid of each landscape design treatment. Overlapping centriods indicate that those treatments are not significantly different from each other. Biplot rays, originating from the grand mean show directions of relative responsiveness in canonical space. (T0=surface, T.025=0.25 m, T.05=0.5 m, T1=1.0 m, T2=2.0 m, T5=5.0 m).

Figure 4a. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during premonsoon 2007 morning (900 to 1000 Hr) in response to four landscape design treatments. Treatments include: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

Below: Canonical correlation analysis. Canonical circles show the 95% confidence intervals around the distribution centroid of each landscape design treatment. Overlapping centriods indicate that those treatments are not significantly different from each other. Biplot rays, originating from the grand mean show directions of relative responsiveness in canonical space. (T0=surface, T.025=0.25 m, T.05=0.5 m, T1=1.0 m, T2=2.0 m, T5=5.0 m).

Table 3.

Synoptic weather conditions during data collection periods. The temperature (°C) is given for the 30-year average and average during data collection. Average relative humidity, shown as a percentage, (RH) and geopotential height (GPH) are given for the data collection period.

Collection Period	Average Temperature (°C) 30 Year	Period	Avg RH (%)	GPH
Pre-monsoon	39.2	39.6	14.4	5890
Monsoon	40.6	40.9	32.0	5870
Winter	21.8	19.7	68.5	5710

Table 4.

Mean percent relative humidity (RH) and saturation vapor pressure (Sat VP) at 2 m during morning, afternoon and evening collection periods pre-monsoon and monsoon 2007 and winter 2008.

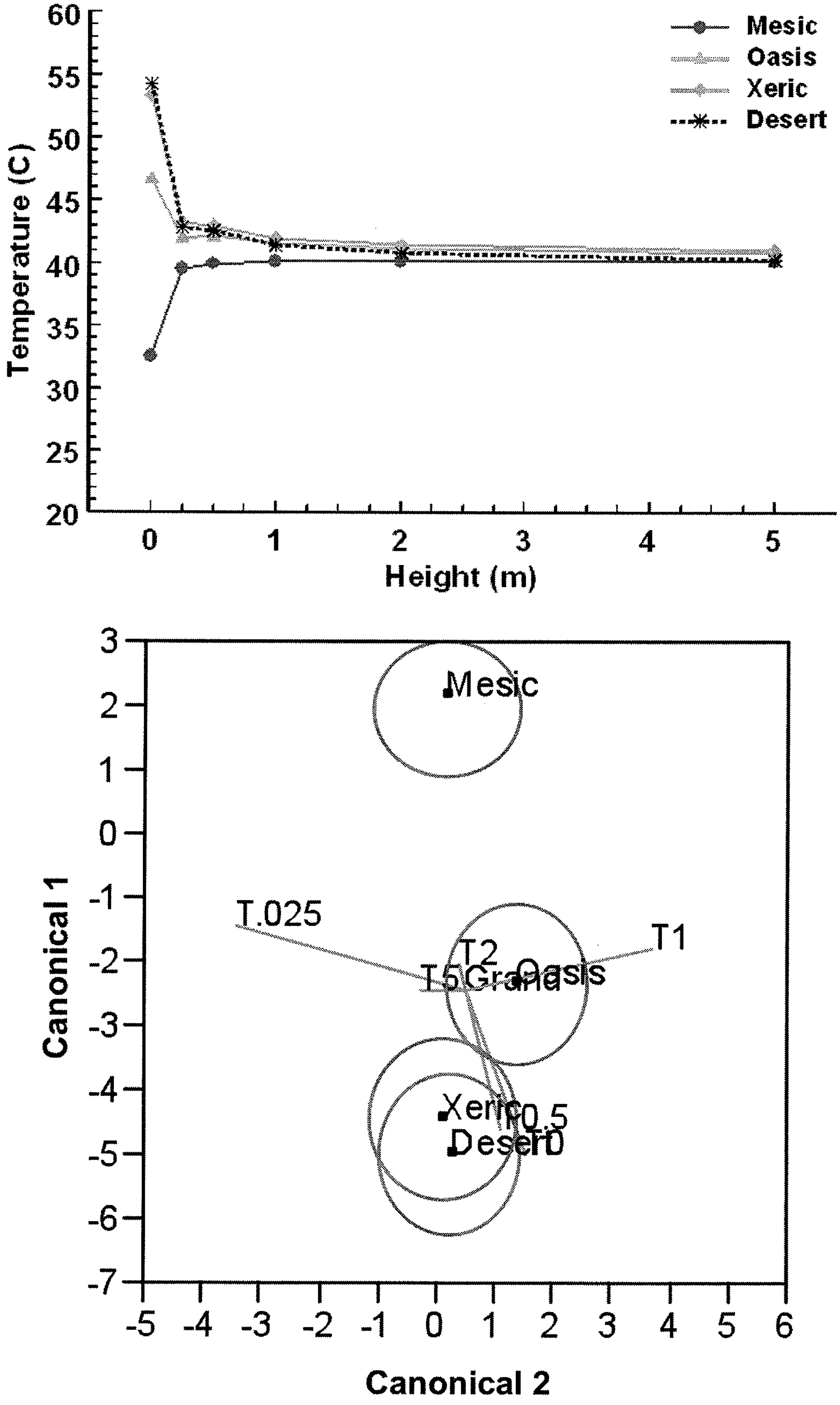
Month Treatment	Morning		Afternoon		Evening	
	RH (%)	Sat VP (kPa)	RH (%)	Sat VP (kPa)	RH (%)	Sat VP (kPa)
Pre-monsoon						
Mesic	13.2 b	7.13 d	10.7 a	7.39 c	21.9 a	4.35 b
Oasis	11.4 c	8.19 a	8.6 c	7.68 b	15.9 c	4.58 a
Xeric	13.8 a	7.33 c	9.2 b	7.95 a	17.4 b	4.59 a
Desert	11.7 c	7.79 b	8.3 c	7.83 ab	13.7 d	4.40 b
Monsoon						
Mesic	28.6 c	5.32 b	18.9 b	7.13 d	24.3 d	4.40 d
Oasis	30.9 b	5.83 a	14.6 d	8.19 a	25.2 c	5.50 a
Xeric	31.2 b	5.37 b	16.8 c	7.33 c	35.8 b	4.65 c
Desert	34.7 a	5.89 a	22.0 a	7.79 b	44.9 a	4.74 b
Winter						
Mesic	59.9 c	1.48 a	31.5 c	2.70 a	61.6 b	1.64 b
Oasis	66.3 b	1.38 b	25.3 d	2.62 b	41.8 c	1.74 a
Xeric	70.6 a	1.14 c	35.2 a	2.14 c	70.1 a	1.31 c
Desert	65.7 b	1.05 d	32.9 b	1.78 d	67.8 a	1.22 d

Values are treatment means, n=40. Treatment means in columns by month followed by the same letter are not significantly different, Tukey's HSD test alpha = 0.05.

all four treatments, mean relative humidity and saturation vapor pressures ranged from 8.3% (desert) to 10.7% (mesic) and 7.39 to 7.95 KPa, respectively (Table 4).

Unlike the pre-monsoon morning or afternoon temperature height profiles, the pre-monsoon evening temperature height profiles for all treatments were generally coolest at the landscape surface (Fig. 4c). Canonical centroid plots and test contrasts between the treatments showed a marginally significant pairing of desert and xeric treatment temperature height profiles (G-G Epsilon P=0.0588) that were both different from the oasis profile (G-G Epsilon P=0.0009) and mesic profiles (G-G Epsilon P=0.0001). Additionally, the mesic and oasis temperature height profiles were significantly different (G-G Epsilon P=0.0001). The greatest difference in adjusted mean temperatures (9°C) during the evening was recorded at the landscape surface between the decomposing granite covered xeric (28°C) and turf grass covered mesic (19°C) treatments. Similar to afternoon air temperatures, treatment-related differences in adjusted mean air temperatures above the surface ranged from 4°C at the 0.025-m height to less than 2°C at the 2-m and 5-m heights. The directions of biplot rays in canonical space for all height variables during the pre-monsoon evening were different (Fig. 4c). Mean relative humidity and saturation vapor pressures across all treatments during the pre-monsoon evening interval ranged from 13.7% (desert) to 21.9% (mesic) and 4.35 to 4.59 KPa, respectively (Table 4).

Figure 4b.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Temperature (C)
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Height (m)
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Canonical 2
Mesic
T.025
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T2
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Grand
Oasis
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Desert
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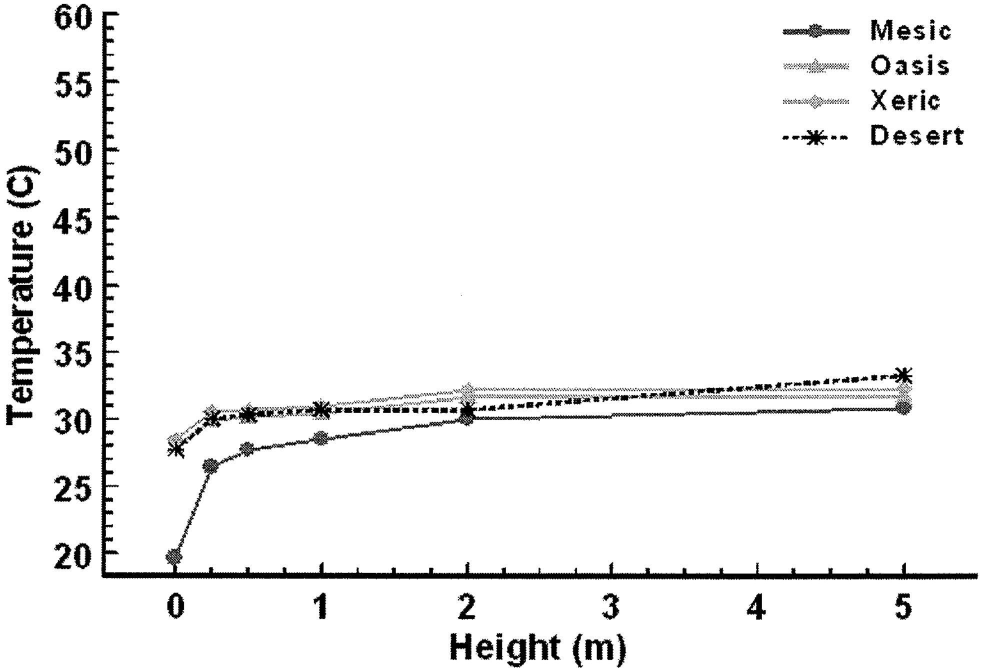
Figure 4b. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during premonsoon 2007 afternoon (1600 to 1700 Hr) in response to four landscape design treatments. Treatments include: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

Below: Canonical correlation analysis. Canonical circles show the 95% confidence intervals around the distribution centroid of each landscape design treatment. Overlapping centriods indicate that those treatments are not significantly different from each other. Biplot rays, originating from the grand mean show directions of relative responsiveness in canonical space. (T0=surface, T.025=0.25 m, T.05=0.5 m, T1=1.0 m, T2=2.0 m, T5=5.0 m).

Figure 4c.


Temperature (C)
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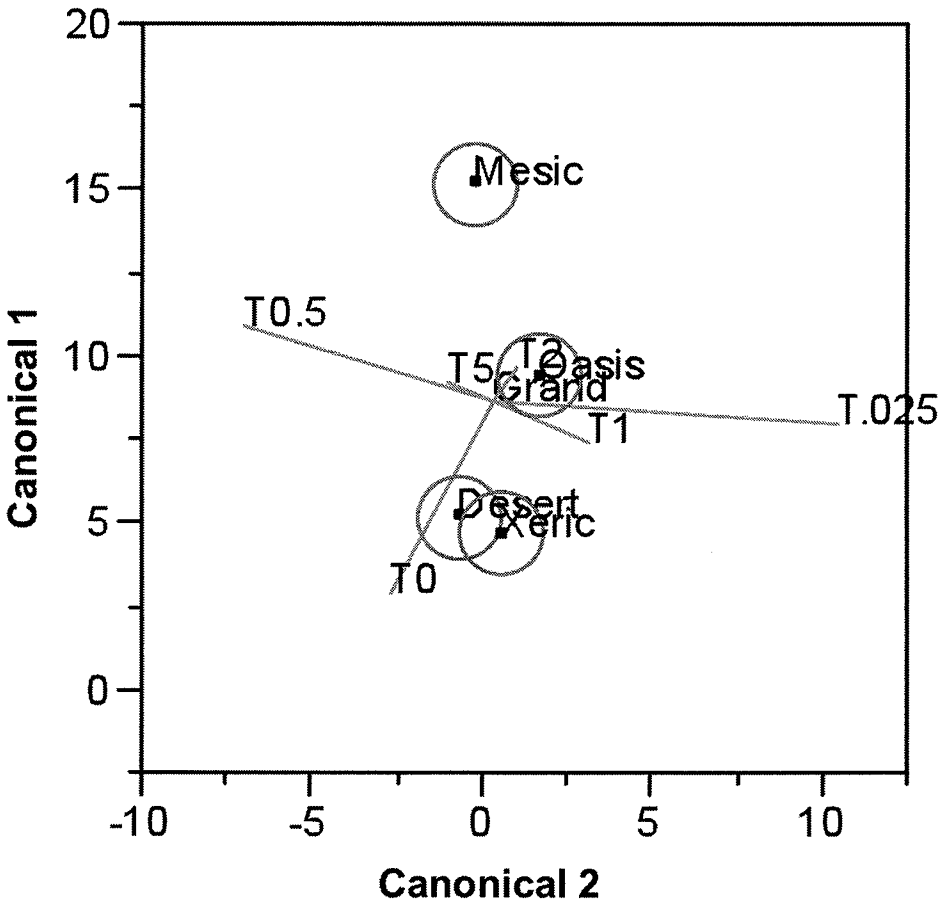
Canonical 1
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Figure 4c. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during premonsoon 2007 evening (2100 to 2200 Hr) in response to four landscape design treatments. Treatments were: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

Below: Canonical correlation analysis. Canonical circles show the 95% confidence intervals around the distribution centroid of each landscape design treatment. Overlapping centriods indicate that those treatments are not significantly different from each other. Biplot rays, originating from the grand mean show directions of relative responsiveness in canonical space. (T0=surface, T.025=0.25 m, T.05=0.5 m, T1=1.0 m, T2=2.0 m, T5=5.0 m).

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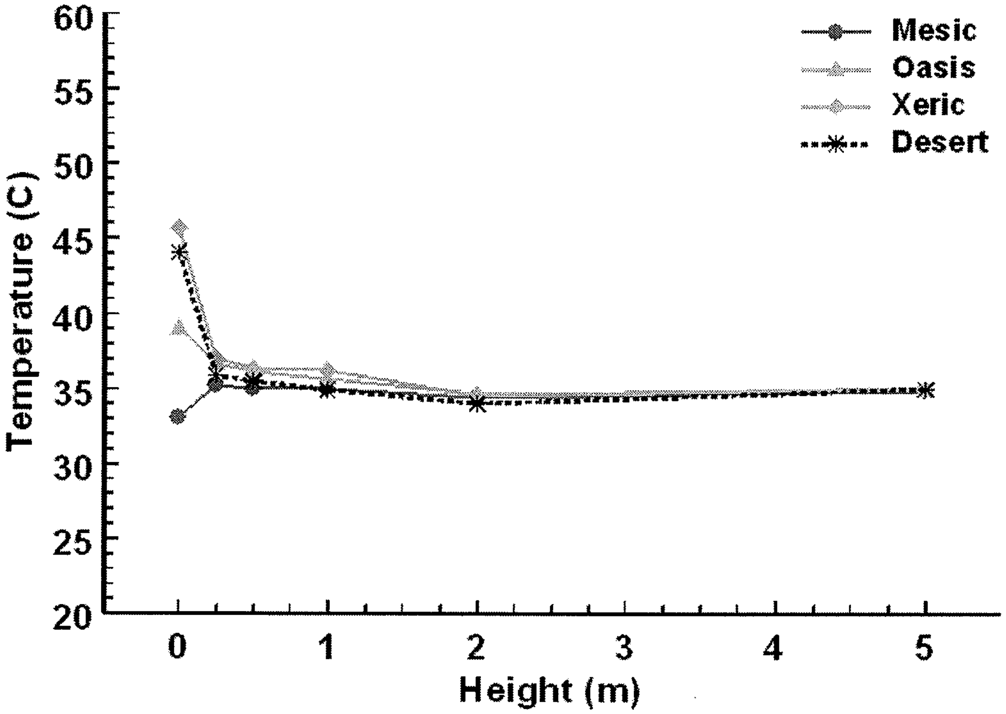
For the monsoon afternoon, canonical centroid plots and test contrasts between the treatments showed a distinct pairing of desert and xeric treatment temperature height profiles (G-G Epsilon P=0.2186) that were both different from the oasis (G-G Epsilon P=0.0003) and mesic (G-G Epsilon P=0.0001) temperature height profiles. Additionally, the mesic and oasis temperature height

Figure 5a.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Mesic
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Xeric
Desert

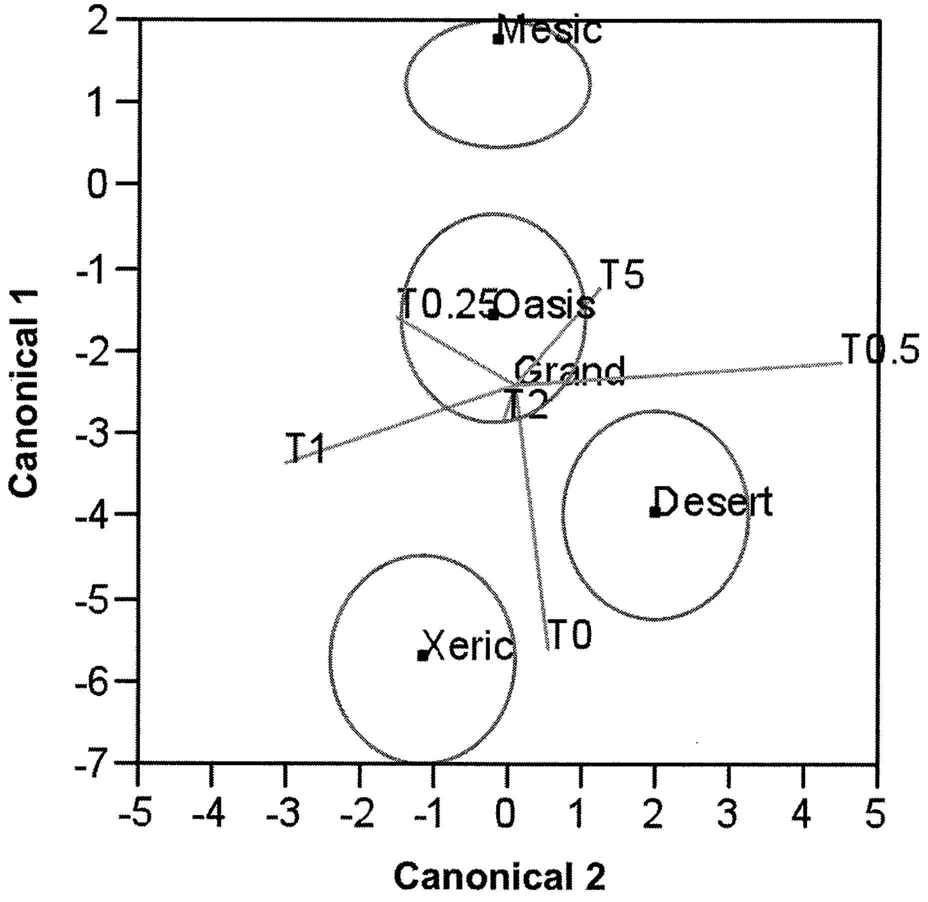
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Figure 5a. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during monsoon 2007 morning (900 to 1000 Hr) in response to four landscape design treatments. Treatments include: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

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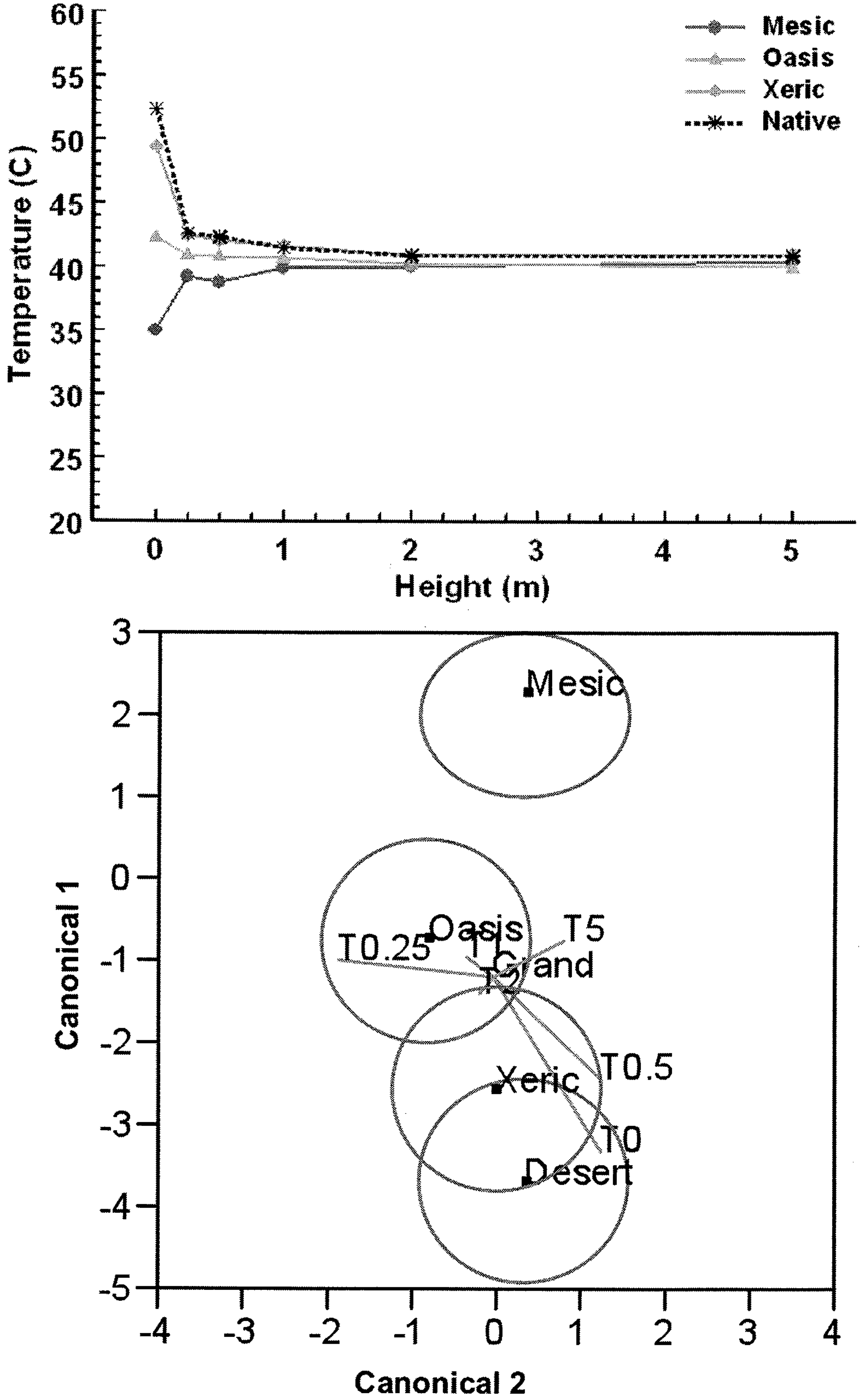
profiles were significantly different (G-G Epsilon P=0.0035). The greatest difference in adjusted mean temperatures during the afternoon was at the landscape surface (18°C) and was recorded between the desert (53°C) and mesic (35°C) treatments. Treatment-related differences in adjusted mean temperatures were 2°C or less between 2-m and 5-m heights. For monsoon afternoon, similarities in the direction of biplot rays within canonical space for height variables were detected for the surface and 0.5-m height (Fig. 5b). Mean relative humidities and saturation vapor pressures across treatments during this morning interval ranged from 14.6% (oasis) to 22.0% (desert) and 7.13 to 8.19 KPa, respectively (Table 4).

For monsoon evening, the temperature profile of the unirrigated, decomposing granite-covered desert landscape treatment showed a virtually constant adjusted air temperature (ca. 32°C) from the surface to 5.0 m height (Fig. 5c). Otherwise, the temperature height profiles of the other treatments exhibited various trends toward decreased temperatures at the surface that were related to the extent of turf grass cover (Fig. 5c). Canonical centroid plots and test contrasts between the treatments showed that the temperature height profiles of each treatment were different from one another (G-G Epsilon P=0.0001). The greatest difference in adjusted mean temperatures was at the landscape surface (13°C) and was recorded between the desert (34°C) and mesic (21°C) treatments. Just like the adjusted air temperatures during the monsoon afternoons, treatment-related differences in adjusted mean temperatures were 2°C or less between 1 m and 5 m (Fig. 5c). For monsoon evenings, a strong dissimilarity within canonical space in the direction of biplot rays for height variables was

Figure 5b.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Xeric
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Desert

Figure 5b. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during monsoon 2007 afternoon (1600 to 1700 Hr) in response to four landscape design treatments. Treatments include: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

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Table 3.

Synoptic weather conditions during data collection periods. The temperature (°C) is given for the 30-year average and average during data collection. Average relative humidity, shown as a percentage, (RH) and geopotential height (GPH) are given for the data collection period.

Collection Period	Average Temperature (°C) 30 Year	Period	Avg RH (%)	GPH
Pre-monsoon	39.2	39.6	14.4	5890
Monsoon	40.6	40.9	32.0	5870
Winter	21.8	19.7	68.5	5710

Table 4.

Mean percent relative humidity (RH) and saturation vapor pressure (Sat VP) at 2 m during morning, afternoon and evening collection periods pre-monsoon and monsoon 2007 and winter 2008.

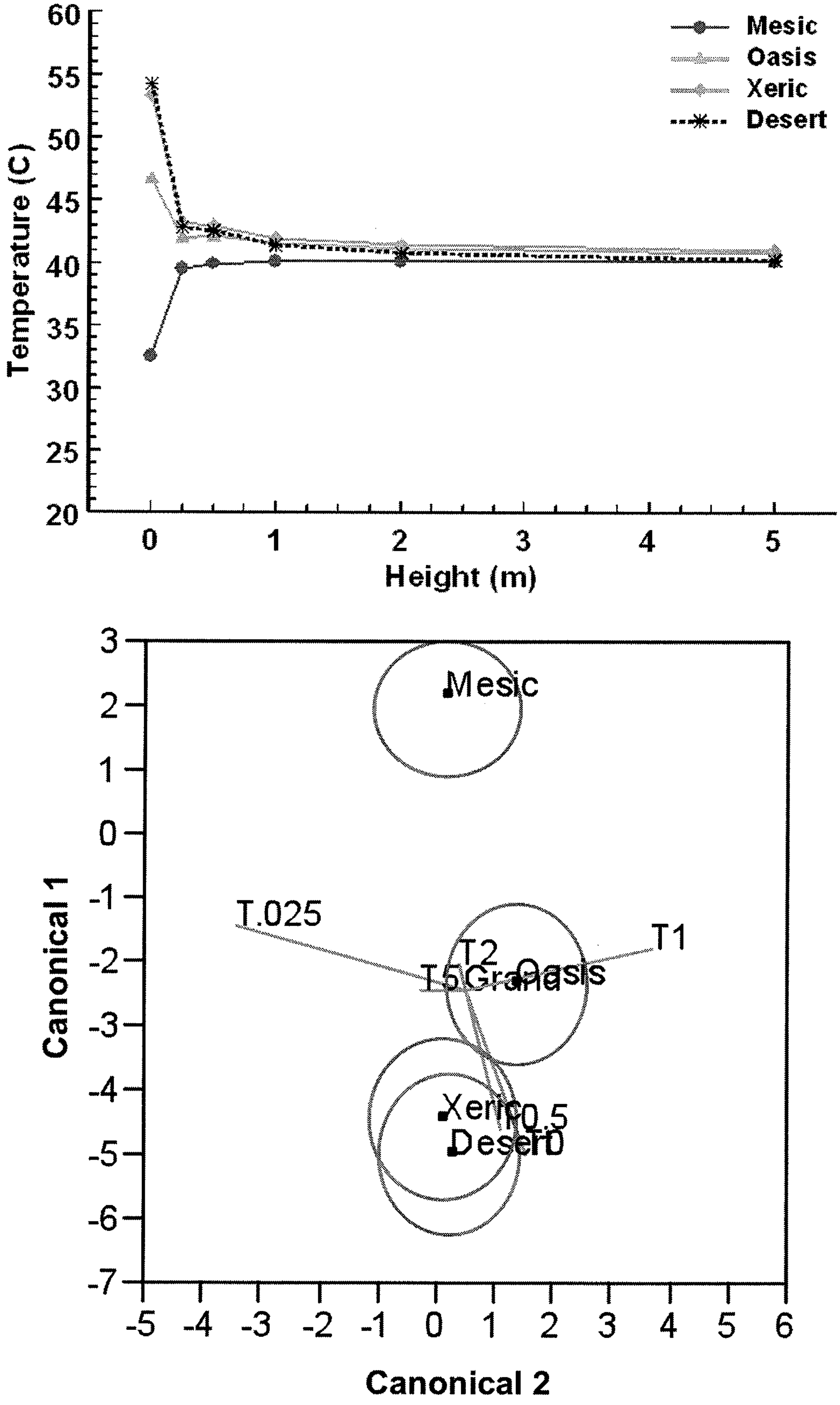
Month Treatment	Morning		Afternoon		Evening	
	RH (%)	Sat VP (kPa)	RH (%)	Sat VP (kPa)	RH (%)	Sat VP (kPa)
Pre-monsoon						
Mesic	13.2 b	7.13 d	10.7 a	7.39 c	21.9 a	4.35 b
Oasis	11.4 c	8.19 a	8.6 c	7.68 b	15.9 c	4.58 a
Xeric	13.8 a	7.33 c	9.2 b	7.95 a	17.4 b	4.59 a
Desert	11.7 c	7.79 b	8.3 c	7.83 ab	13.7 d	4.40 b
Monsoon						
Mesic	28.6 c	5.32 b	18.9 b	7.13 d	24.3 d	4.40 d
Oasis	30.9 b	5.83 a	14.6 d	8.19 a	25.2 c	5.50 a
Xeric	31.2 b	5.37 b	16.8 c	7.33 c	35.8 b	4.65 c
Desert	34.7 a	5.89 a	22.0 a	7.79 b	44.9 a	4.74 b
Winter						
Mesic	59.9 c	1.48 a	31.5 c	2.70 a	61.6 b	1.64 b
Oasis	66.3 b	1.38 b	25.3 d	2.62 b	41.8 c	1.74 a
Xeric	70.6 a	1.14 c	35.2 a	2.14 c	70.1 a	1.31 c
Desert	65.7 b	1.05 d	32.9 b	1.78 d	67.8 a	1.22 d

Values are treatment means, n=40. Treatment means in columns by month followed by the same letter are not significantly different, Tukey's HSD test alpha = 0.05.

all four treatments, mean relative humidity and saturation vapor pressures ranged from 8.3% (desert) to 10.7% (mesic) and 7.39 to 7.95 KPa, respectively (Table 4).

Unlike the pre-monsoon morning or afternoon temperature height profiles, the pre-monsoon evening temperature height profiles for all treatments were generally coolest at the landscape surface (Fig. 4c). Canonical centroid plots and test contrasts between the treatments showed a marginally significant pairing of desert and xeric treatment temperature height profiles (G-G Epsilon P=0.0588) that were both different from the oasis profile (G-G Epsilon P=0.0009) and mesic profiles (G-G Epsilon P=0.0001). Additionally, the mesic and oasis temperature height profiles were significantly different (G-G Epsilon P=0.0001). The greatest difference in adjusted mean temperatures (9°C) during the evening was recorded at the landscape surface between the decomposing granite covered xeric (28°C) and turf grass covered mesic (19°C) treatments. Similar to afternoon air temperatures, treatment-related differences in adjusted mean air temperatures above the surface ranged from 4°C at the 0.025-m height to less than 2°C at the 2-m and 5-m heights. The directions of biplot rays in canonical space for all height variables during the pre-monsoon evening were different (Fig. 4c). Mean relative humidity and saturation vapor pressures across all treatments during the pre-monsoon evening interval ranged from 13.7% (desert) to 21.9% (mesic) and 4.35 to 4.59 KPa, respectively (Table 4).

Figure 4b.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Temperature (C)
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Canonical 2
Mesic
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Desert
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Figure 4b. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during premonsoon 2007 afternoon (1600 to 1700 Hr) in response to four landscape design treatments. Treatments include: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

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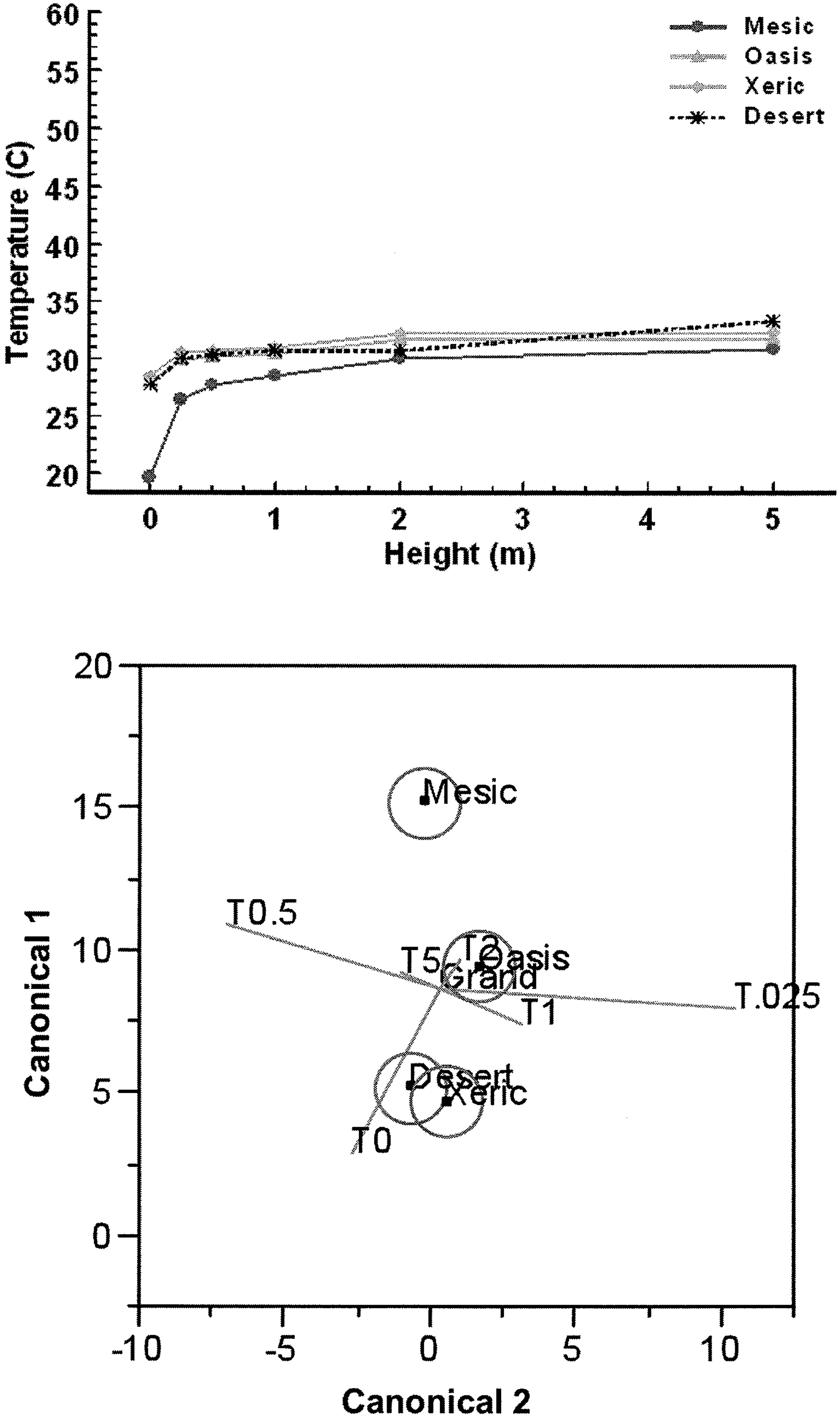
Figure 4c.


Mesic
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Mesic
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Oasis
T5
Grand
T1
T.025
Desert
Xeric
T0

Figure 4c. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during premonsoon 2007 evening (2100 to 2200 Hr) in response to four landscape design treatments. Treatments were: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

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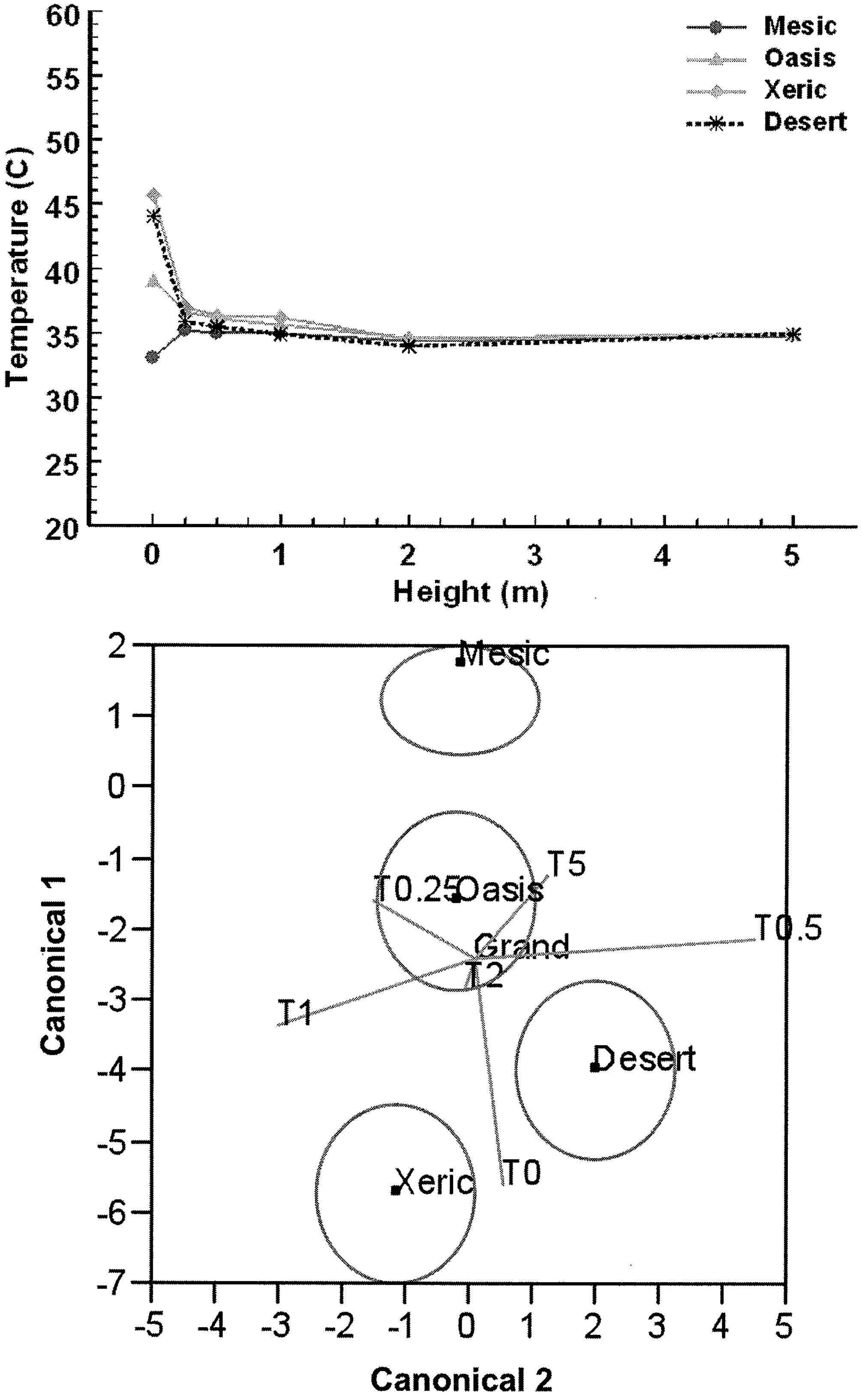
Figure 5a.


Mesic
Oasis
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Desert
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Canonical 2

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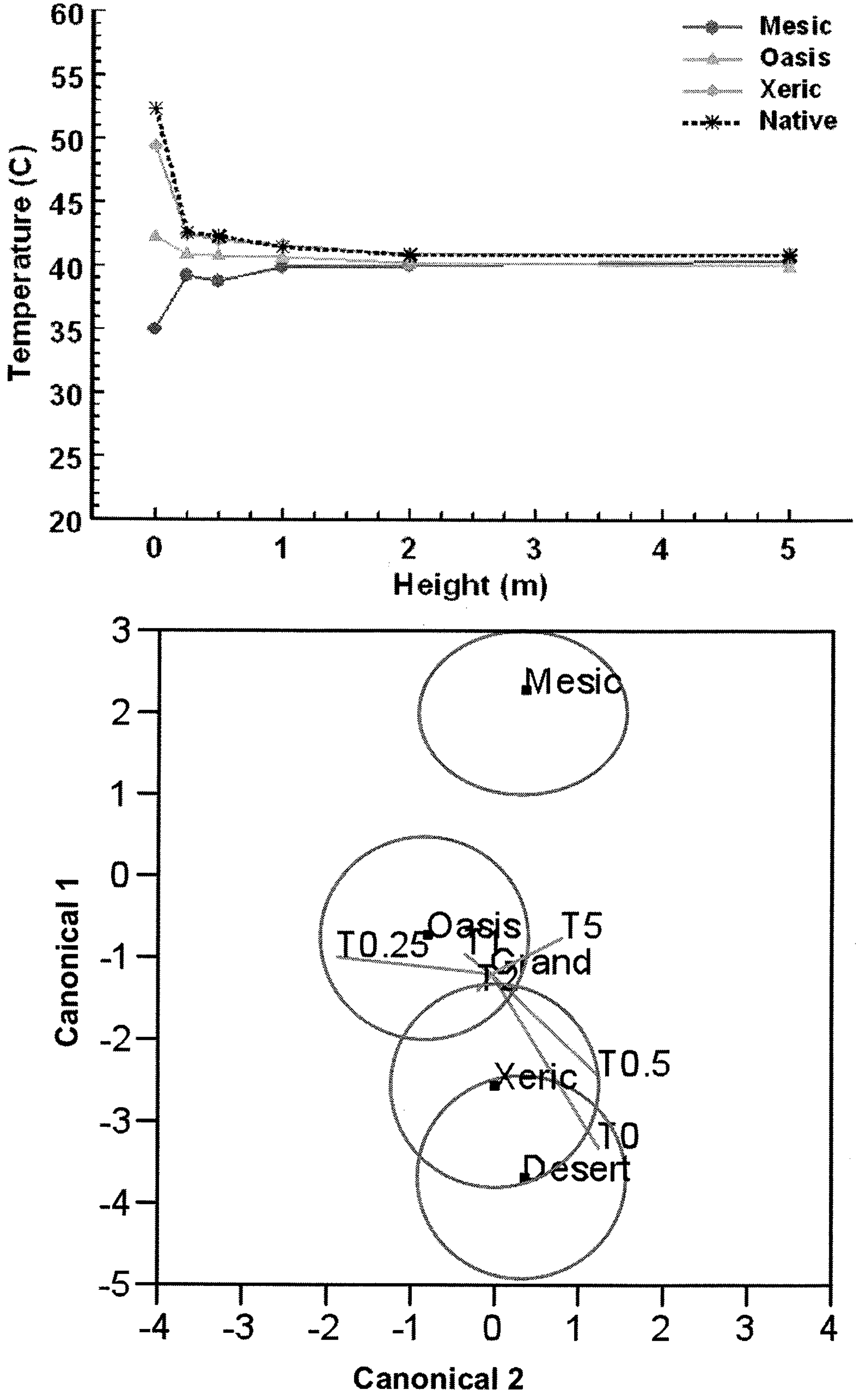
For monsoon evening, the temperature profile of the unirrigated, decomposing granite-covered desert landscape treatment showed a virtually constant adjusted air temperature (ca. 32°C) from the surface to 5.0 m height (Fig. 5c). Otherwise, the temperature height profiles of the other treatments exhibited various trends toward decreased temperatures at the surface that were related to the extent of turf grass cover (Fig. 5c). Canonical centroid plots and test contrasts between the treatments showed that the temperature height profiles of each treatment were different from one another (G-G Epsilon P=0.0001). The greatest difference in adjusted mean temperatures was at the landscape surface (13°C) and was recorded between the desert (34°C) and mesic (21°C) treatments. Just like the adjusted air temperatures during the monsoon afternoons, treatment-related differences in adjusted mean temperatures were 2°C or less between 1 m and 5 m (Fig. 5c). For monsoon evenings, a strong dissimilarity within canonical space in the direction of biplot rays for height variables was

Figure 5b.


Mesic
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Canonical 2

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Table 3.

Synoptic weather conditions during data collection periods. The temperature (°C) is given for the 30-year average and average during data collection. Average relative humidity, shown as a percentage, (RH) and geopotential height (GPH) are given for the data collection period.

	Average Temperature (°C)			
Collection Period	30 Year	Period	Avg RH (%)	GPH
Pre-monsoon	39.2	39.6	14.4	5890
Monsoon	40.6	40.9	32.0	5870
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Mean percent relative humidity (RH) and saturation vapor pressure (Sat VP) at 2 m during morning, afternoon and evening collection periods pre-monsoon and monsoon 2007 and winter 2008.

Month Treatment	Morning		Afternoon		Evening	
	RH (%)	Sat VP (kPa)	RH (%)	Sat VP (kPa)	RH (%)	Sat VP (kPa)
Pre-monsoon						
Mesic	13.2 b	7.13 d	10.7 a	7.39 c	21.9 a	4.35 b
Oasis	11.4 c	8.19 a	8.6 c	7.68 b	15.9 c	4.58 a
Xeric	13.8 a	7.33 c	9.2 b	7.95 a	17.4 b	4.59 a
Desert	11.7 c	7.79 b	8.3 c	7.83 ab	13.7 d	4.40 b
Monsoon						
Mesic	28.6 c	5.32 b	18.9 b	7.13 d	24.3 d	4.40 d
Oasis	30.9 b	5.83 a	14.6 d	8.19 a	25.2 c	5.50 a
Xeric	31.2 b	5.37 b	16.8 c	7.33 c	35.8 b	4.65 c
Desert	34.7 a	5.89 a	22.0 a	7.79 b	44.9 a	4.74 b
Winter						
Mesic	59.9 c	1.48 a	31.5 c	2.70 a	61.6 b	1.64 b
Oasis	66.3 b	1.38 b	25.3 d	2.62 b	41.8 c	1.74 a
Xeric	70.6 a	1.14 c	35.2 a	2.14 c	70.1 a	1.31 c
Desert	65.7 b	1.05 d	32.9 b	1.78 d	67.8 a	1.22 d

Values are treatment means, n=40. Treatment means in columns by month followed by the same letter are not significantly different, Tukey's HSD test alpha = 0.05.

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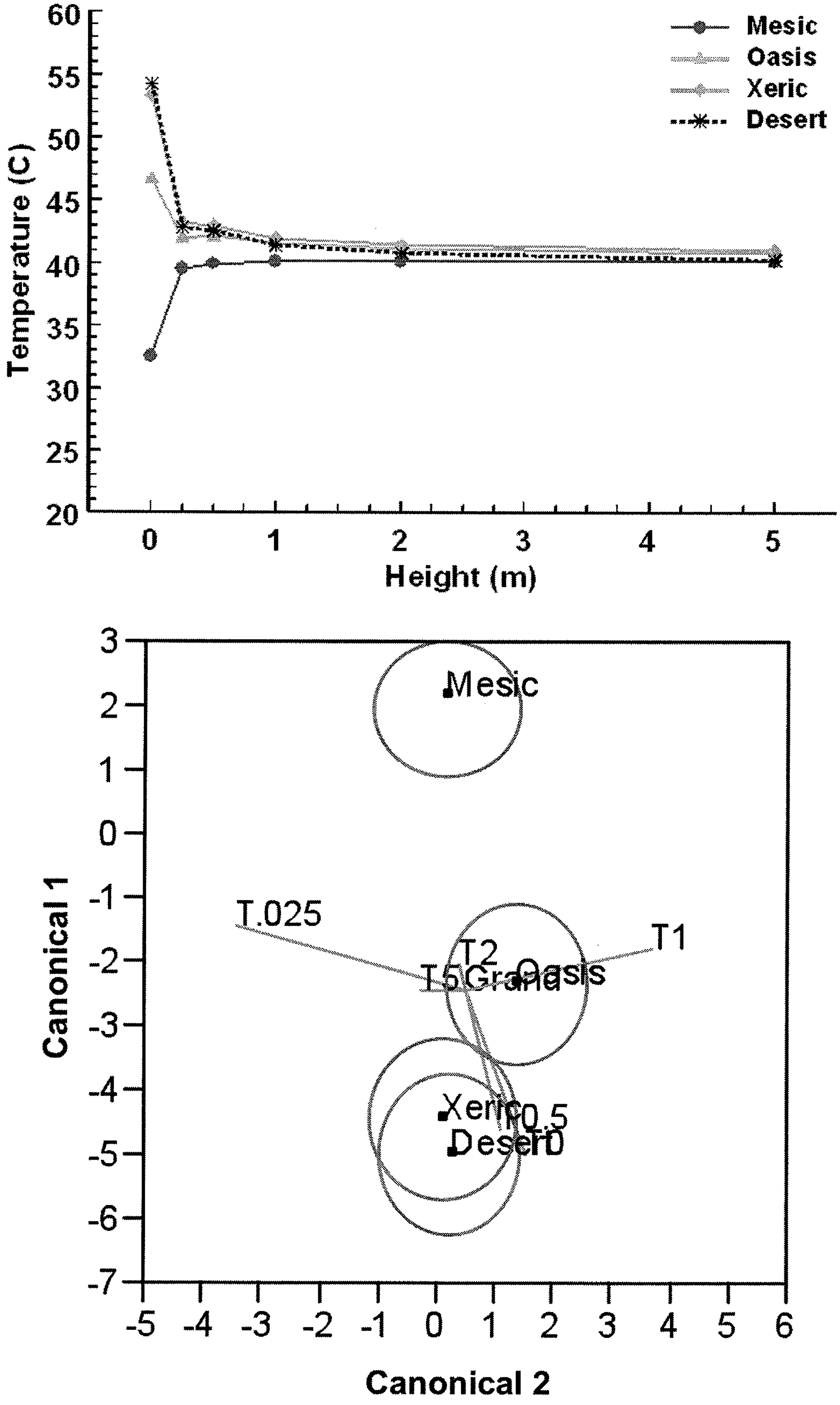
Figure 4b.


Mesic
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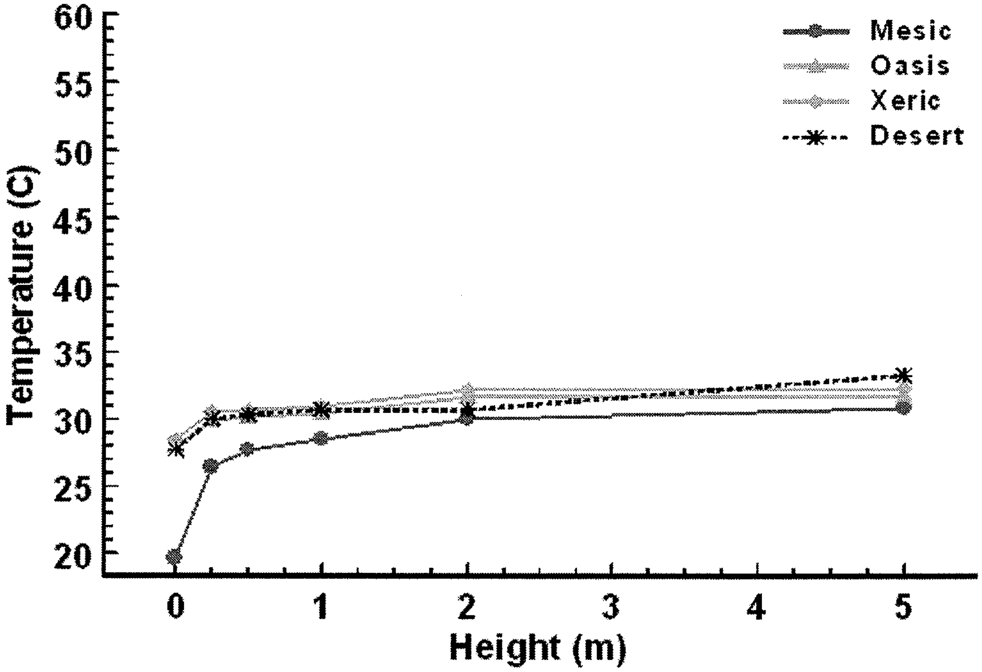
6
Canonical 2

Figure 4b. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during premonsoon 2007 afternoon (1600 to 1700 Hr) in response to four landscape design treatments. Treatments include: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

Below: Canonical correlation analysis. Canonical circles show the 95% confidence intervals around the distribution centroid of each landscape design treatment. Overlapping centriods indicate that those treatments are not significantly different from each other. Biplot rays, originating from the grand mean show directions of relative responsiveness in canonical space. (T0=surface, T.025=0.25 m, T.05=0.5 m, T1=1.0 m, T2=2.0 m, T5=5.0 m).

Figure 4c.


Temperature (C)
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3
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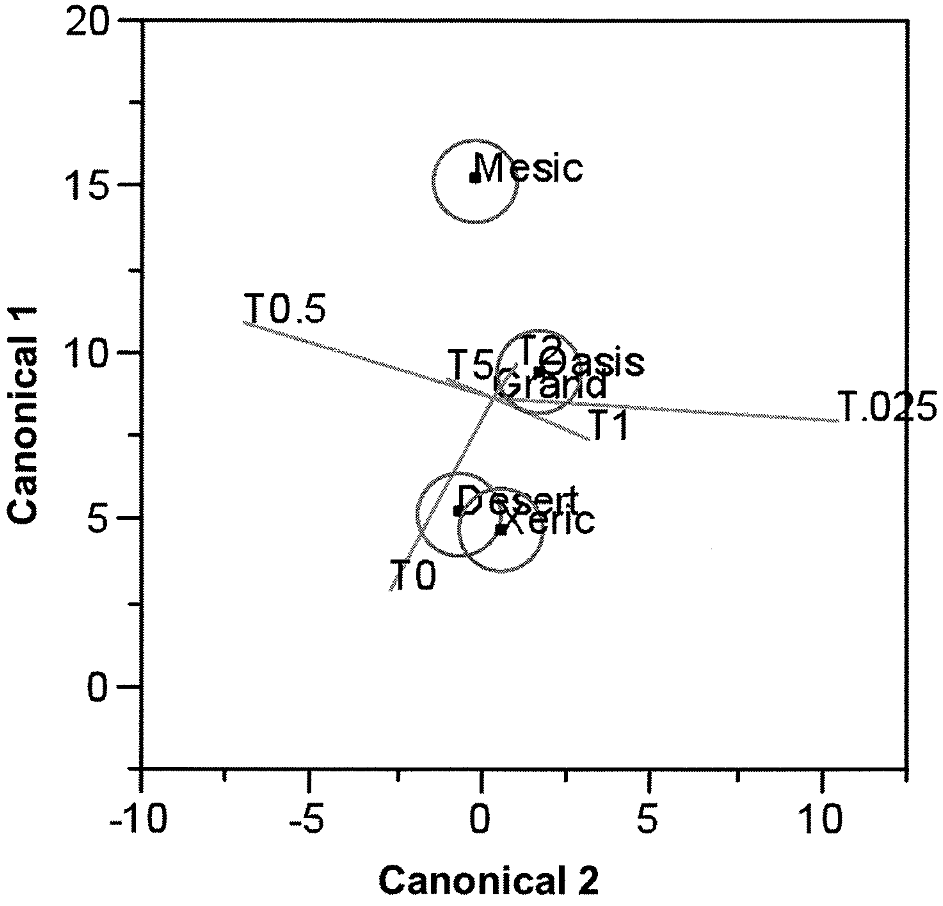
Height (m)
Mesic
Oasis
Xeric
Desert


Canonical 1
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-5
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Canonical 2
Mesic
T0.5
T2
Oasis
T5
Grand
T1
T.025
Desert
Xeric
T0

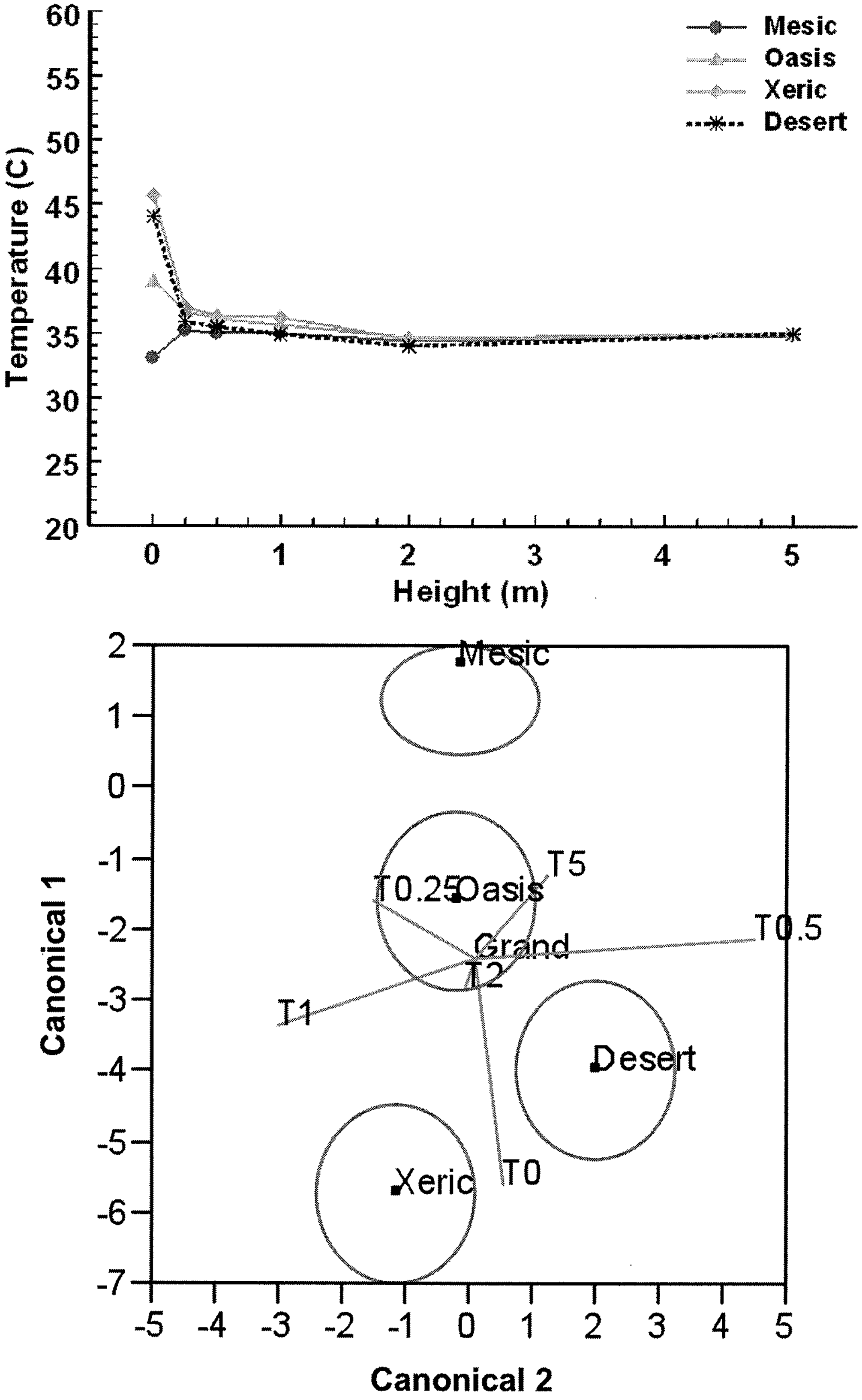
Figure 4c. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during premonsoon 2007 evening (2100 to 2200 Hr) in response to four landscape design treatments. Treatments were: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

Below: Canonical correlation analysis. Canonical circles show the 95% confidence intervals around the distribution centroid of each landscape design treatment. Overlapping centriods indicate that those treatments are not significantly different from each other. Biplot rays, originating from the grand mean show directions of relative responsiveness in canonical space. (T0=surface, T.025=0.25 m, T.05=0.5 m, T1=1.0 m, T2=2.0 m, T5=5.0 m).

Monsoon 2007. Repeated measures analyses of data collected during the morning, afternoon, and evening intervals showed that residential landscape design treatments affected temperature height profiles most extensively in the range of 0 to 2 meters above the landscape surface (Fig. 5a-c). For the monsoon morning interval, canonical centroid plots and test contrasts between the treatments revealed a distinct pairing of desert and xeric treatment temperature height profiles (G-G Epsilon P=0.4162) that were both different from the oasis and mesic profiles (G-G Epsilon P=0.0001) (Fig. 5a). Additionally, the mesic and oasis temperature height profiles were significantly different (G-G Epsilon P=0.0001). The greatest difference in adjusted mean temperatures (13°C) during the evening was recorded at the landscape surface between the decomposing granite-covered xeric (46°C) and turf grass-covered mesic (33°C) treatments. In contrast, treatment-related differences in adjusted mean air temperatures between the 0.25-m and 5-m heights were 2°C or less. The directions within canonical space of biplot rays for all height variables during the pre-monsoon morning were different (Fig. 5a). Mean relative humidities and saturation vapor pressures across treatments during this morning interval ranged from 28.6% (mesic) to 34.7% (desert) and 5.32 to 5.89 KPa, respectively (Table 4).

For the monsoon afternoon, canonical centroid plots and test contrasts between the treatments showed a distinct pairing of desert and xeric treatment temperature height profiles (G-G Epsilon P=0.2186) that were both different from the oasis (G-G Epsilon P=0.0003) and mesic (G-G Epsilon P=0.0001) temperature height profiles. Additionally, the mesic and oasis temperature height

Figure 5a.


Mesic
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Temperature (C)
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Height (m)
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Oasis
T0.25
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Desert
Xeric
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Canonical 1
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Canonical 2

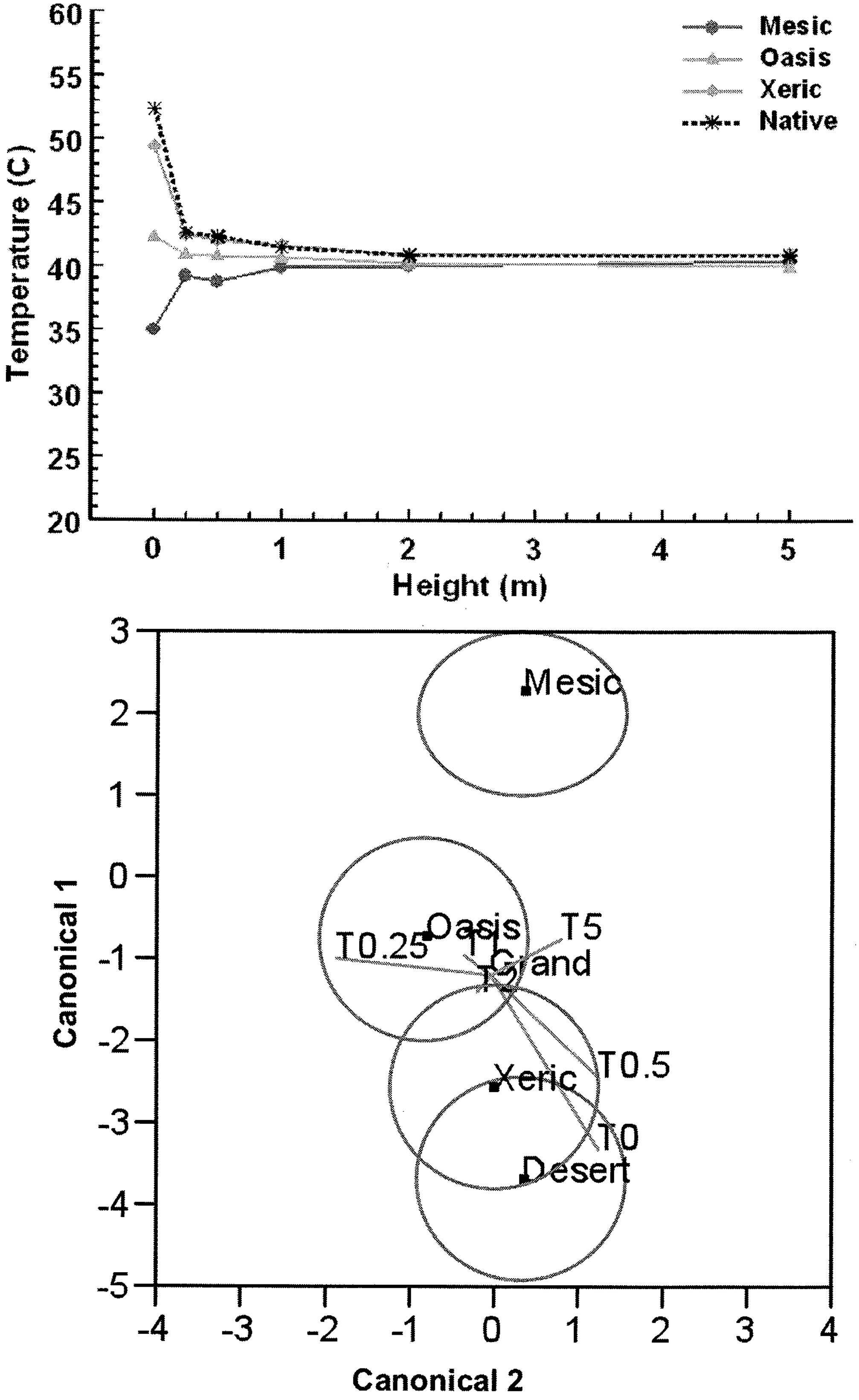
Figure 5a. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during monsoon 2007 morning (900 to 1000 Hr) in response to four landscape design treatments. Treatments include: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

Below: Canonical correlation analysis. Canonical circles show the 95% confidence intervals around the distribution centroid of each landscape design treatment. Overlapping centriods indicate that those treatments are not significantly different from each other. Biplot rays, originating from the grand mean show directions of relative responsiveness in canonical space. (T0=surface, T.025=0.25 m, T.05=0.5 m, T1=1.0 m, T2=2.0 m, T5=5.0 m).

profiles were significantly different (G-G Epsilon P=0.0035). The greatest difference in adjusted mean temperatures during the afternoon was at the landscape surface (18°C) and was recorded between the desert (53°C) and mesic (35°C) treatments. Treatment-related differences in adjusted mean temperatures were 2°C or less between 2-m and 5-m heights. For monsoon afternoon, similarities in the direction of biplot rays within canonical space for height variables were detected for the surface and 0.5-m height (Fig. 5b). Mean relative humidities and saturation vapor pressures across treatments during this morning interval ranged from 14.6% (oasis) to 22.0% (desert) and 7.13 to 8.19 KPa, respectively (Table 4).

For monsoon evening, the temperature profile of the unirrigated, decomposing granite-covered desert landscape treatment showed a virtually constant adjusted air temperature (ca. 32°C) from the surface to 5.0 m height (Fig. 5c). Otherwise, the temperature height profiles of the other treatments exhibited various trends toward decreased temperatures at the surface that were related to the extent of turf grass cover (Fig. 5c). Canonical centroid plots and test contrasts between the treatments showed that the temperature height profiles of each treatment were different from one another (G-G Epsilon P=0.0001). The greatest difference in adjusted mean temperatures was at the landscape surface (13°C) and was recorded between the desert (34°C) and mesic (21°C) treatments. Just like the adjusted air temperatures during the monsoon afternoons, treatment-related differences in adjusted mean temperatures were 2°C or less between 1 m and 5 m (Fig. 5c). For monsoon evenings, a strong dissimilarity within canonical space in the direction of biplot rays for height variables was

Figure 5b.


Temperature (C)
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Canonical 2
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T5
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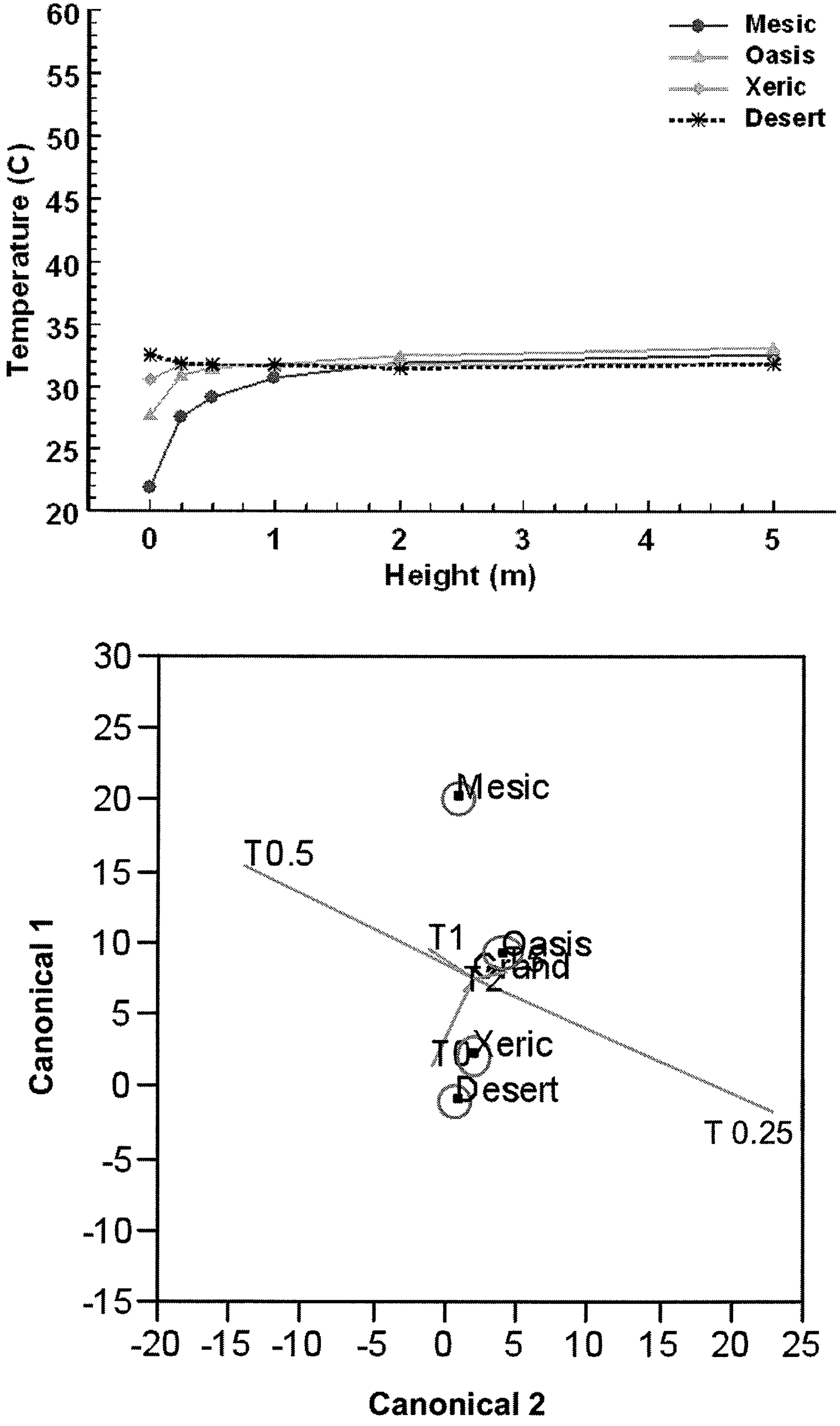
T0.5
Xeric
T0
Desert

Figure 5b. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during monsoon 2007 afternoon (1600 to 1700 Hr) in response to four landscape design treatments. Treatments include: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

Below: Canonical correlation analysis. Canonical circles show the 95% confidence intervals around the distribution centroid of each landscape design treatment. Overlapping centriods indicate that those treatments are not significantly different from each other. Biplot rays, originating from the grand mean show directions of relative responsiveness in canonical space. (T0=surface, T.025=0.25 m, T.05=0.5 m, T1=1.0 m, T2=2.0 m, T5=5.0 m).

Figure 5c.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Temperature (C)
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Height (m)
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Oasis
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Desert
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Canonical 1
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10
15
20
25
Canonical 2
Mesic
T0.5
T1
Oasis
Grand
T2
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Xeric
Desert
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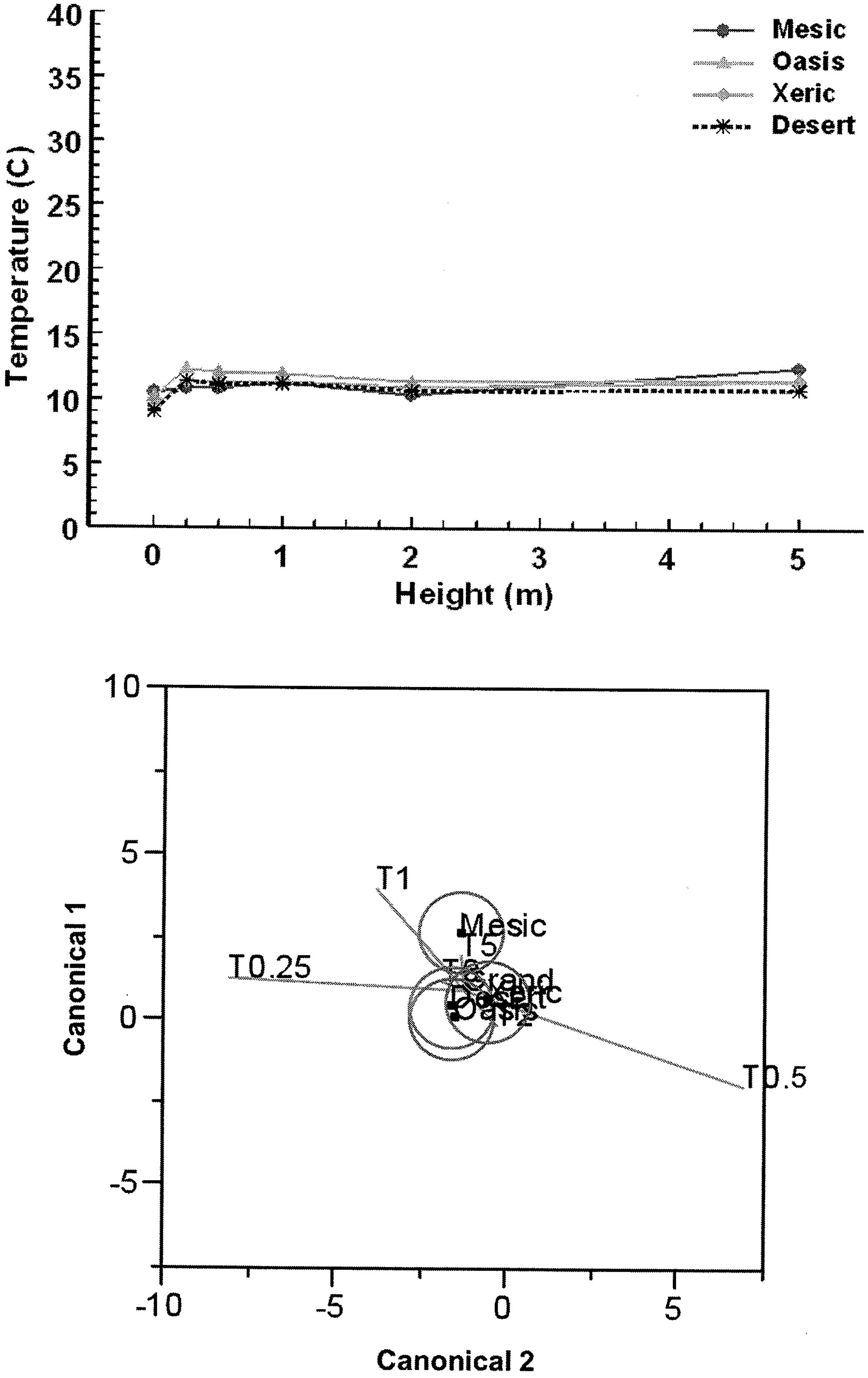
Figure 5c. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during monsoon 2007 evening (2100 to 2200 Hr) in response to four landscape design treatments. Treatments include: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

Below: Canonical correlation analysis. Canonical circles show the 95% confidence intervals around the distribution centroid of each landscape design treatment. Overlapping centriods indicate that those treatments are not significantly different from each other. Biplot rays, originating from the grand mean show directions of relative responsiveness in canonical space. (T0=surface, T.025=0.25 m, T.05=0.5 m, T1=1.0 m, T2=2.0 m, T5=5.0 m).

detected for the 0.25-m and 0.5-m heights (Fig. 5c). Mean relative humidities and saturation vapor pressures across treatments during the monsoon evenings ranged from 24.3% (mesic) to 44.9% (desert) and 4.40 to 5.50 KPa, respectively (Table 4).

Winter 2008. Repeated measures analyses of the data showed differences by time of day in the way landscape design treatments affected temperature height profiles (Fig. 6a-c). For mornings, the temperature height profiles of all four landscape design treatments were visually similar (Fig. 6a) — as indicated by slightly lower adjusted mean temperatures on the surface and then a relatively constant adjusted mean temperature over a small range between 0.25-m to 5.0-m heights. In fact, treatment-related differences in the winter morning adjusted mean temperatures were 2°C or less at all heights. Canonical centroid plots and test contrasts between the treatments showed distinct pairings of desert and xeric treatments (G-G Epsilon P=0.8017), desert and oasis treatments (G-G Epsilon P=0.8871), and xeric and oasis treatments (G-G Epsilon P=0.6648). Even though the mesic treatment profile was statistically significantly different from the clustered group of desert, xeric, and oasis treatment profiles (G-G Epsilon P=0.0137), a visual assessment of the data does not reflect this. For winter mornings, strong dissimilarities in the direction of biplot rays within canonical space were detected between the 0.5-m and the 0.25-m and 1 m heights (Fig. 6a). Across all treatments, mean relative humidities and saturation vapor pressures ranged from 59.9% (mesic) to 70.6% (xeric) and 1.05 to 1.48 KPa, respectively (Table 4).

Figure 6a.


Mesic
Oasis
Xeric
Desert
Temperature (C)
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Height (m)
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Canonical 1
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-5
Canonical 2
-10
-5
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5
T1
Mesic
T5
T0.25
T6
Grand
Xeric
Desert
Oasis
T2
T0.5

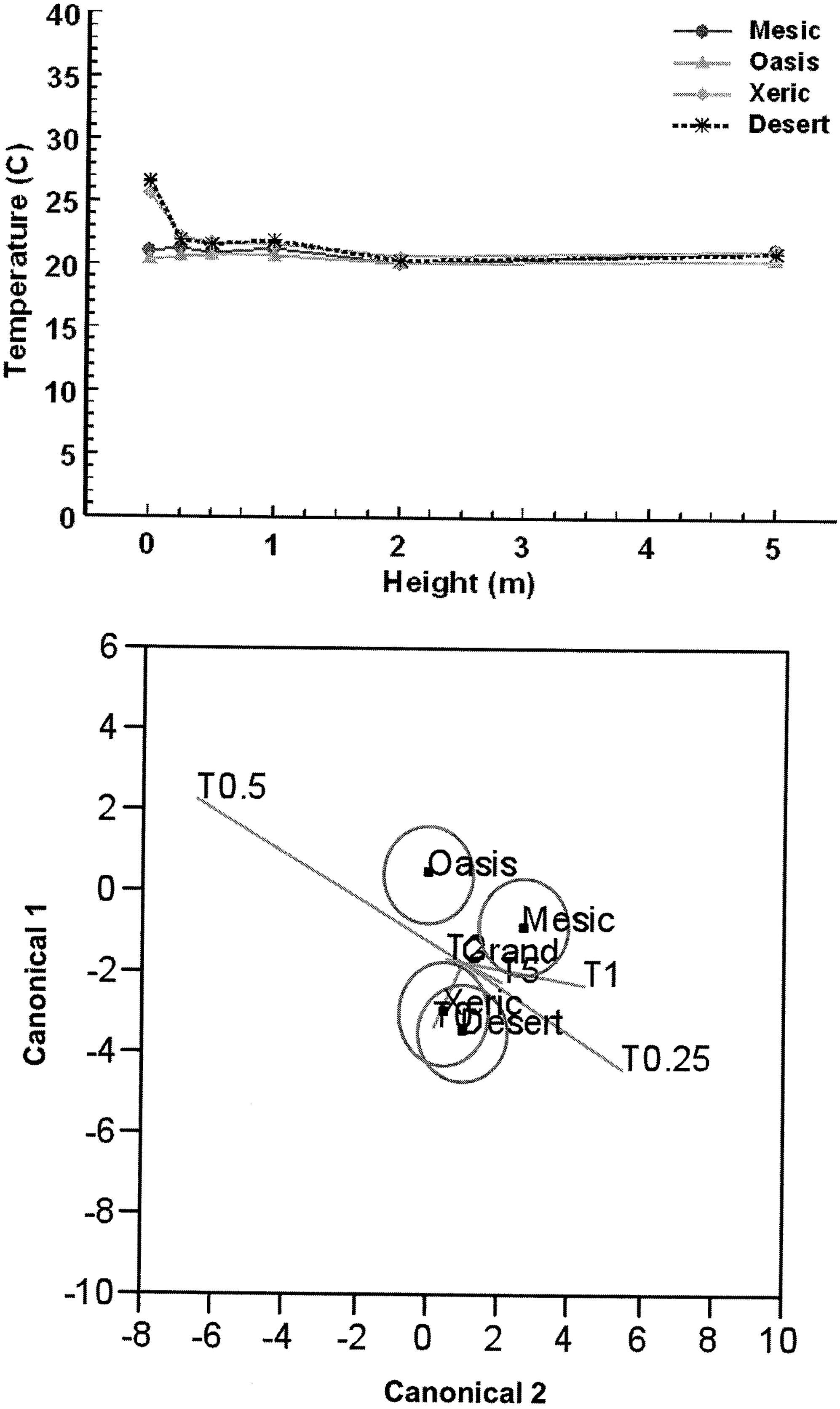
Figure 6a. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during February 2008 morning (900 to 1000 Hr) in response to four landscape design treatments. Treatments were: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch). Mean temperatures adjusted for variance in synoptic weather conditions during data collection period.

Below: Canonical correlation analysis. Circles show the 95% confidence intervals around the distribution centroid of each landscape design treatment. Overlapping centriods indicate that those treatments are not significantly different from each other, whereas non-overlapping centroids indicate a difference. Biplot rays, originating from the grand mean show directions of relative responsiveness in canonical space. (T0=surface, T.025=0.25 m, T.05=0.5 m, T1=1.0 m, T2=2.0 m, T5=5.0 m).

For winter afternoon, temperature height profiles were affected by landscape design treatment most extensively at the landscape surface, but to a lesser extent than was found during the afternoon hours during either pre-monsoon or monsoon 2007 (Fig. 6b). Canonical centroid plots and test contrasts between the treatments showed a distinct pairing of desert and xeric treatment temperature height profiles (G-G Epsilon P=0.5291) that were both different from the oasis or mesic profiles (G-G Epsilon P=0.0001). Moreoever, the mesic and oasis temperature height profiles also showed a distinct pairing (G-G Epsilon P=0.8360). The greatest difference in mean adjusted temperatures (6°C) was recorded at the landscape surface between the desert (27°C) and oasis (21°C) treatments. In contrast, treatment-related differences in mean adjusted temperatures at the 2-m and 5-m heights were 1°C or less. For winter afternoons, strong dissimilarities within canonical space in the direction of biplot rays were detected for the 0.25-m and the 0.5-m heights (Fig. 6b). Mean relative humidities and saturation vapor pressures across all treatments during the afternoon ranged from 25.3% (oasis) to 35.2% (xeric) and 1.78 to 2.70 KPa, respectively (Table 4).

For winter evenings, the temperature height profiles of all treatments exhibited certain trends toward decreased temperatures close too and at the surface that were related to the the extent of turf grass cover (Fig. 6c). Canonical centroid plots and test contrasts between the treatments showed a distinct pairing of desert and xeric treatment temperature height profiles (G-G Epsilon

Figure 6b.


Temperature (C)
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Mesic
Oasis
Xeric
Desert
0
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4
5
Height (m)
6
4
2
0
-2
-4
-6
-8
-10
Canonical 1
T0.5
Oasis
Mesic
TGrand
T5
T1
Xeric
T0
Desert
T0.25
-8
-6
-4
-2
0
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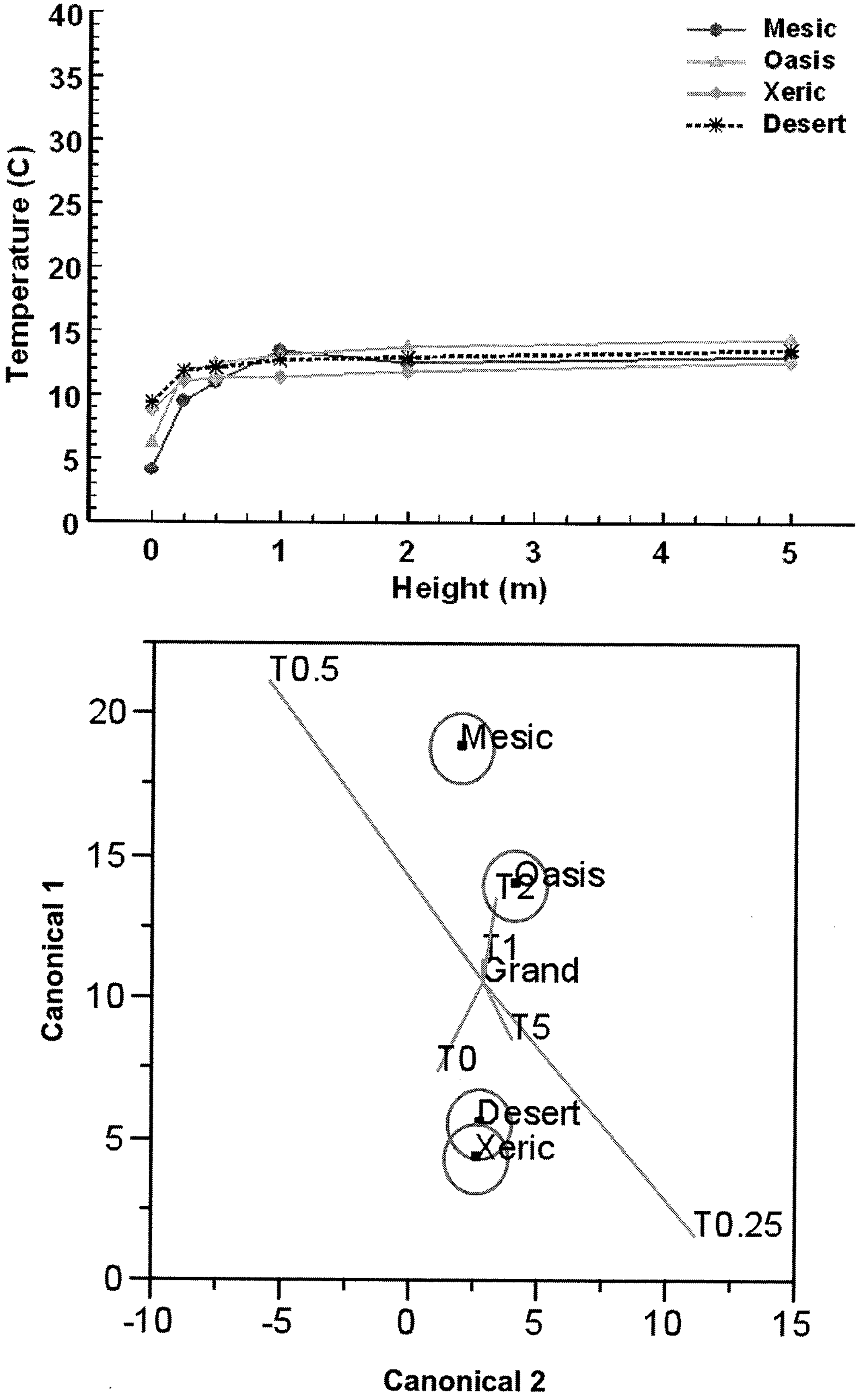
6
8
10
Canonical 2

Figure 6b. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during winter 2008 afternoon (1600 to 1700 Hr) in response to four landscape design treatments. Treatments include: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

Below: Canonical correlation analysis. Canonical circles show the 95% confidence intervals around the distribution centroid of each landscape design treatment. Overlapping centriods indicate that those treatments are not significantly different from each other. Biplot rays, originating from the grand mean show directions of relative responsiveness in canonical space. (T0=surface, T.025=0.25 m, T.05=0.5 m, T1=1.0 m, T2=2.0 m, T5=5.0 m).

Figure 6c.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Temperature (C)
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Height (m)
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Canonical 1
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Canonical 2

Figure 6c. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during winter 2008 evening (2100 to 2200 Hr) in response to four landscape design treatments. Treatments include: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

Below: Canonical correlation analysis. Canonical circles show the 95% confidence intervals around the distribution centroid of each landscape design treatment. Overlapping centriods indicate that those treatments are not significantly different from each other. Biplot rays, originating from the grand mean show directions of relative responsiveness in canonical space. (T0=surface, T.025=0.25 m, T.05=0.5 m, T1=1.0 m, T2=2.0 m, T5=5.0 m).

P=0.7768) that were both significantly different from the oasis or mesic profiles (G-G Epsilon P=0.0001). Additionally, the mesic and oasis temperature height profiles showed moderate similarity (G-G Epsilon P=0.1081). The greatest differences in mean adjusted temperatures (5°C) occurred at the landscape surface and were recorded between the desert (9°C) and mesic (4°C) treatments. In contrast, treatment-related differences in mean adjusted air temperature between 1 m and 5 m were only about 3°C. Similar to winter afternoons, strong dissimilarities in the direction of biplot rays within canonical space were detected for winter evenings at the 0.25-m and the 0.5-m heights (Fig. 6c). Across all treatments, mean relative humidities and saturation vapor pressures ranged from 41.8% (oasis) to 70.1% (xeric) and 1.22 to 1.74 KPa, respectively (Table 4).

Chapter 4

Discussion And Conclusions

Residential landscape designs found in the Phoenix metropolitan area vary across a gradient of water usage, which influences plant selection, plant placement and overall style of the landscape. The four design styles utilized in this research represent four archetypes along that gradient. Understanding the relationship between the landscape design style and its affect on the immediately surrounding air temperatures will lead to more informed decisions about landscape design in the area. The purpose of this research was to determine the extent to which landscape design style affects vertical air temperatures at the neighborhood scale across three seasons. This research was conducted during pre-monsoon and monsoon conditions of 2007 and winter 2008 on days that had clear, calm anticylonic synoptic weather conditions.

Previous research examining the relationship between surface and air temperatures have utilized a combination of remote sensing, fixed meteorological stations or automobile-mounted transects (Gallo and Owen 1999, Hafner and Kidder, 1999, Stoll and Brazel 1992). In contrast, this study captured a more complete temperature profile through the under canopy layer. The major finding of this research indicated that neighborhoods landscaped with portions of irrigated turf had air temperatures that were noticeably cooler at near surface elevations.

The annual mean evapotranspiration in the Phoenix area is 1,843 mm of water. In contrast, the annual mean precipitation is 147 mm of water (The Arizona Meteorological Network, 2010). As a result, supplemental irrigation is required in the Phoenix area to maintain most residential landscapes. Efforts to reduce the amount of supplemental irrigation necessary have lead to a wide variety of landscape designs, including a diversity of low water-use plant taxa, planting densities and inorganic surface mulch cover types.

The effect of turfgrass as a landscape surface cover in the mesic and oasis treatments, during pre-monsoon summer conditions, which are hot and dry, was to reduce air temperature at elevations up to approximately 2.0 meters. This effect was most pronounced during the middle of the day, due to latent heat transfer from evaporative cooling. The vertical range of the influence observed in the mesic and oasis treatment was less than the 5.0 m originally hypothesized.

The turfgrass in the mesic treatment received 222.6 $l/m^2/month$ supplemental water as irrigation during pre-monsoon conditions. During the same time period, the turfgrass-covered portion of the oasis treatment received approximately 458.3 $l/m^2/month$. The difference in irrigation rates was a result of differences in the precipitation rates of the different sprinkler types used to irrigate the turfgrass in the two treatments. The sprinkler heads in the mesic treatment were solely stream rotor heads, while the sprinkler heads in the oasis treatment were both stream rotor heads in the common areas and conventional overhead spray heads around in the turf areas near the houses. Spray heads

delivered water at a much higher rate, which explains the difference in irrigation rates between the mesic and oasis treatment.

During monsoon summer conditions, which were hot and more humid than pre-monsoon conditions, the effect of turfgrass as a surface cover in the mesic and oasis treatments displayed a similar, but less pronounced pattern on air temperature cooling. These results supported the hypothesis that microclimate effects as a result of landscape design would be decreased during monsoon conditions.

In comparison to pre-monsoon irrigation rates, the turfgrass in the mesic treatment received 281.7 l/m^2 during monsoon conditions and the turfgrass portion of the oasis treatment was irrigated at a rate of 392.2 l/m^2. Although irrigation rates were similar in pre-monsoon and monsoon conditions, increased atmospheric humidity suppressed the capacity for evaporative cooling in the landscape which resulted in reduced air temperatures in the treatments with turfgrass at elevations up to approximately one meter. Spronken-Smith and Oke (1998) found evaporative cooling in parks to have a greater effect on air temperatures in Sacramento, California than in Vancouver, British Columbia. Relative humidities were not reported, but Spronken-Smith et al. (2000) describe Sacramento's climate as "hot and dry", much like pre-monsoon conditions in Phoenix. It is not unreasonable to assume relative humidity to be a contributing factor in limiting the evaporative cooling potential of turfed areas.

For the most part, there was very little difference in relative humidity (2 m height) across the treatments, regardless of season. The two exceptions are during the monsoon night collection period in the desert treatment, and the winter night collection period in the oasis treatment. The higher humidity in the desert treatment during the monsoon night collection period is due to the large irrigation event that was occurring before and during the data collection period at an adjacent golf course. The lower humidity in the oasis treatment during the winter night collection period is the result of natural variation in synoptic weather conditions.

The evaportranspiration (ETo) during the winter data collection was 14.5 mm. In comparison, the pre-monsoon ETo was 40.4 mm and monsoon ETo was 142.2 mm. Irrigation was determined by daily ETo rates and as a result, irrigation during the winter collection period was minimal. Limited water additions to the landscape in connection with less incoming solar radiation meant there was very little evaportanspirational cooling in the treatments during the winter. Spronken-Smith et al. (2000) suggest turfed park areas act like large, wet leaves in "thermostating" surrounding air temperatures, such that during peak heat input, temperatures of irrigated surfaces may be much lower than the air above it. The temperature profiles show that irrigated treatments had much lower surface temperatures than the synoptic air temperatures and un-irrigated treatments have surface temperatures that are much higher than the synoptic air temperatures.

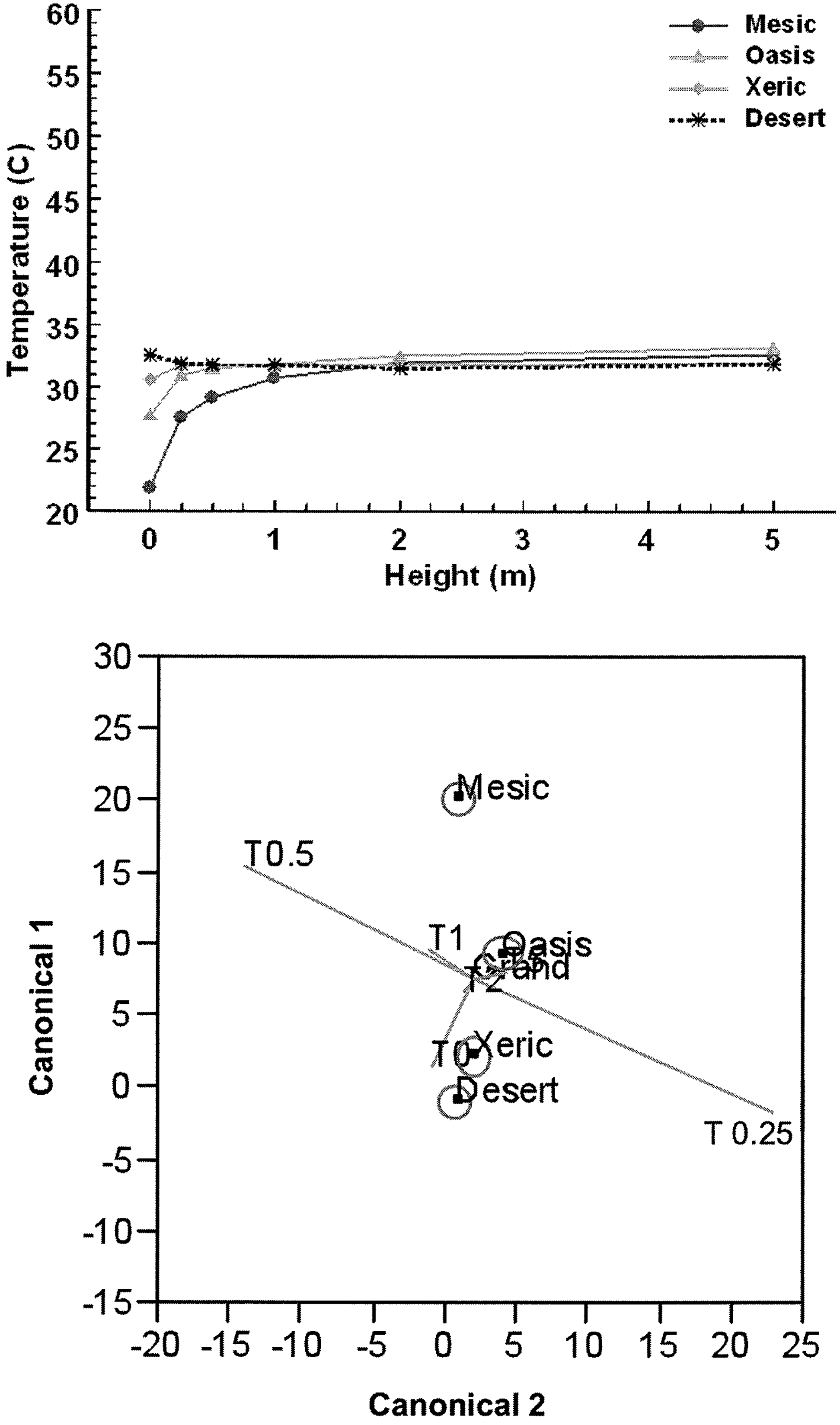
The results of this study indicate that for residential neighborhoods, the strategic use of turfgrass will provide the benefit of heat mitigation in the region of human activity during the summer months, especially during the hot and dry conditions that dominate Arizona summers. However, unoverseeded landscapes will not impact air temperatures during winter, when heat mitigation is not desirable. Homeowners who wish to maximize the heat mitigation utility of their landscapes but limit water consumption should plant judicious amounts of summer lawns in areas of high human activity. Spronken-Smith and Oke (1998) found that the horizontal influence of parks on air temperature extended into the surrounding area approximately the same width of the park. Results of this study indicate that in the Phoenix climate, surface cover is the dominant influence on near-surface air temperatures. However, since widespread turf, such as found in the mesic treatment, is impractical in the current culture which promotes water conservation, it is desirable to create residential landscape designs that maximize heat mitigation while limiting water consumption. Consequently, more research on the widespread effect of different size turf fragments would provide insights useful for residential landscape designers.

Additionally, this research was conducted on immature landscapes. At the time of data collection, the treatments were only three years old. As a result, shade from the small, young trees did not have a noticeable impact on surface or air temperatures. Research which incorporates the effect of mature shade trees

on microclimates in the Phoenix region will allow for even better landscape design recommendations.

Because this research utilized air temperatures throughout the vertical profile, it will be useful to connect in situ temperatures with data collected through remote sensing. Doing so will enable the creation of better, more accurate models for explaining and predicting the UHI. Current mesoscale models, such as WRF (Weather Research and Forcasting, 2010), are commonly used to predict weather in cities and across regions but are unable to capture fine scale differences within urban settings (The Weather Research & Forecasting Model, 2010). The data presented in this study provide the fine scale resolution in temperature patterns that occur because of differences in landscape design at the neighborhood scale.

Figure 5c.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Canonical 2
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T2
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Xeric
Desert
T 0.25

Figure 5c. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during monsoon 2007 evening (2100 to 2200 Hr) in response to four landscape design treatments. Treatments include: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

Below: Canonical correlation analysis. Canonical circles show the 95% confidence intervals around the distribution centroid of each landscape design treatment. Overlapping centriods indicate that those treatments are not significantly different from each other. Biplot rays, originating from the grand mean show directions of relative responsiveness in canonical space. (T0=surface, T.025=0.25 m, T.05=0.5 m, T1=1.0 m, T2=2.0 m, T5=5.0 m).

detected for the 0.25-m and 0.5-m heights (Fig. 5c). Mean relative humidities and saturation vapor pressures across treatments during the monsoon evenings ranged from 24.3% (mesic) to 44.9% (desert) and 4.40 to 5.50 KPa, respectively (Table 4).

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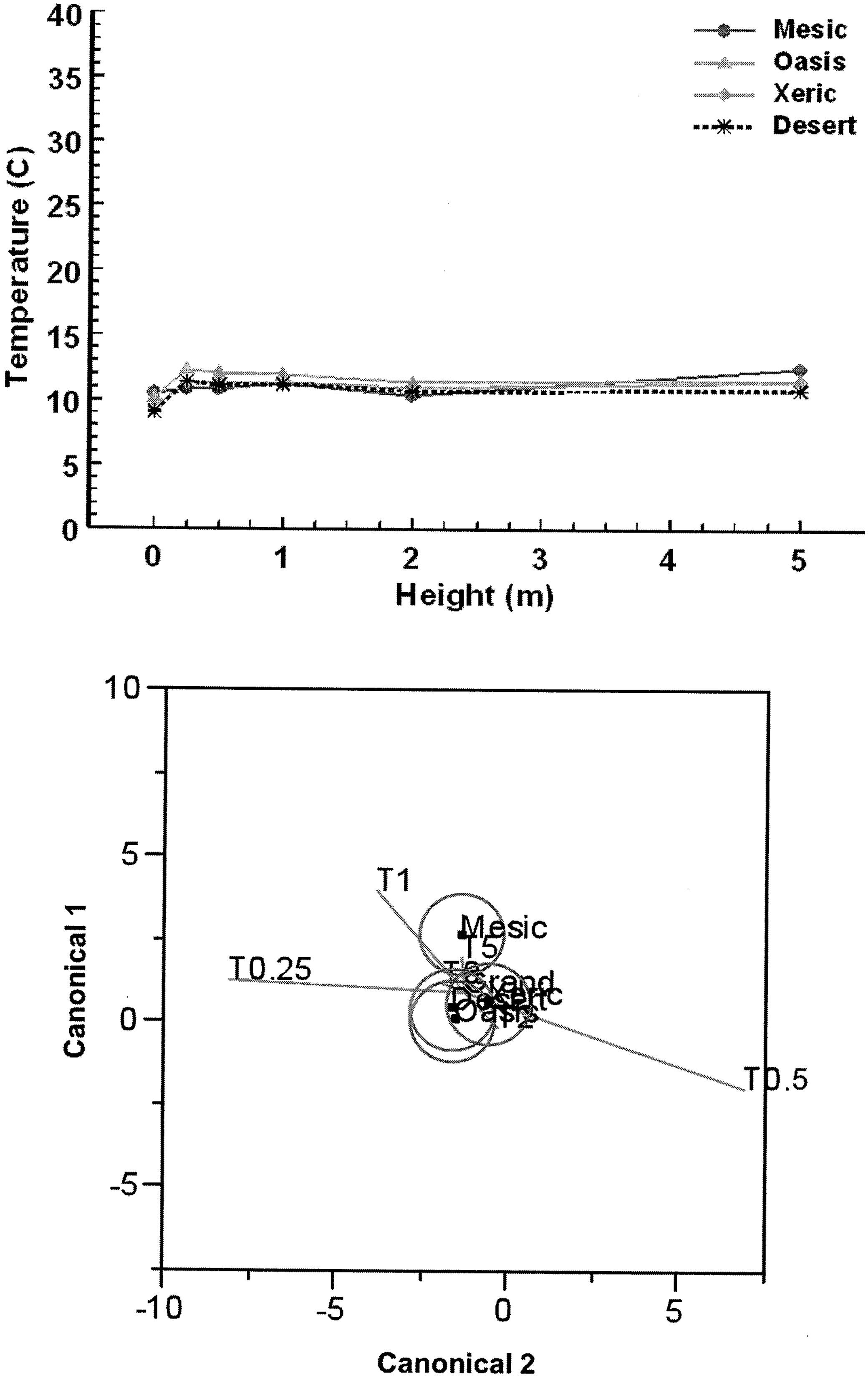
Figure 6a.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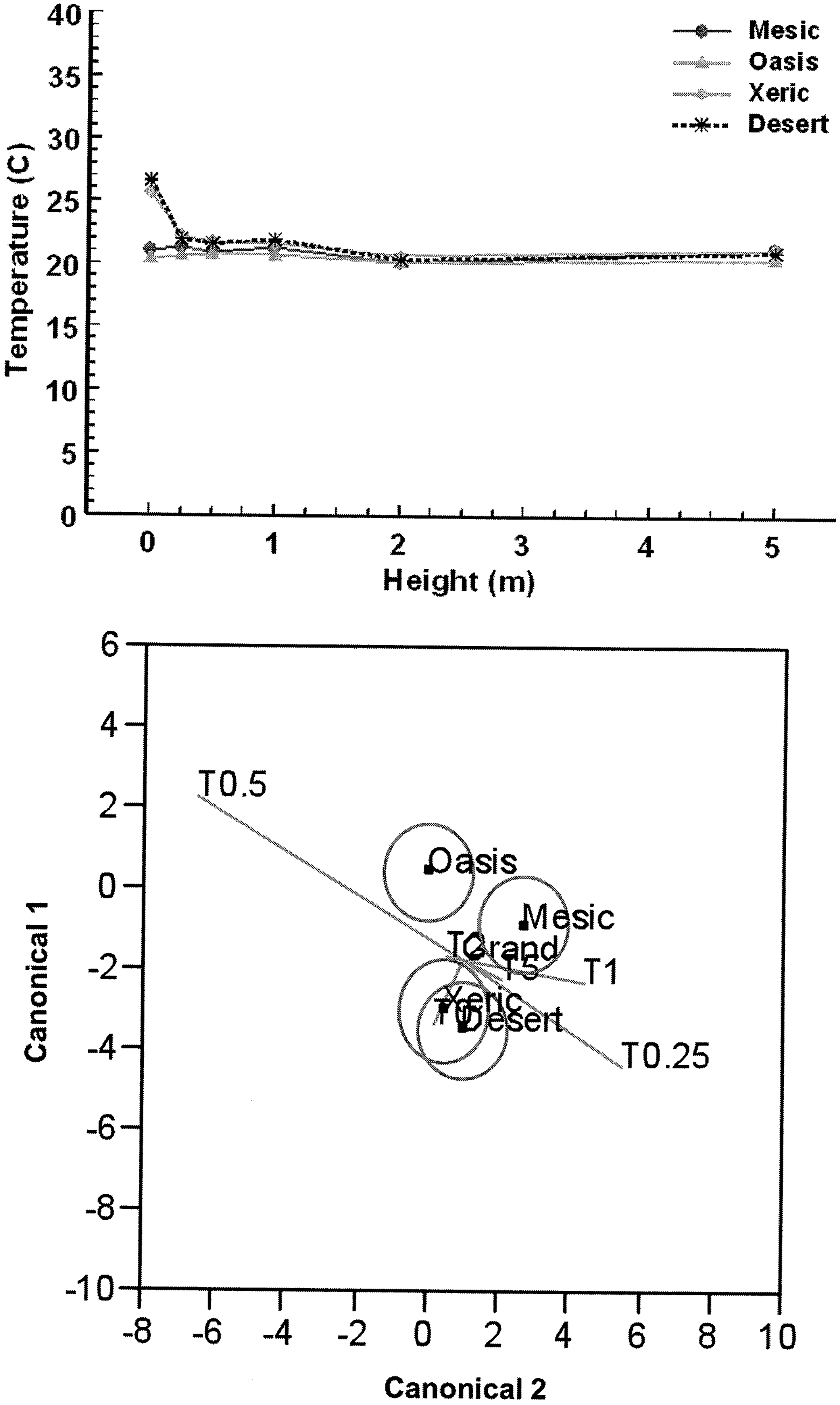
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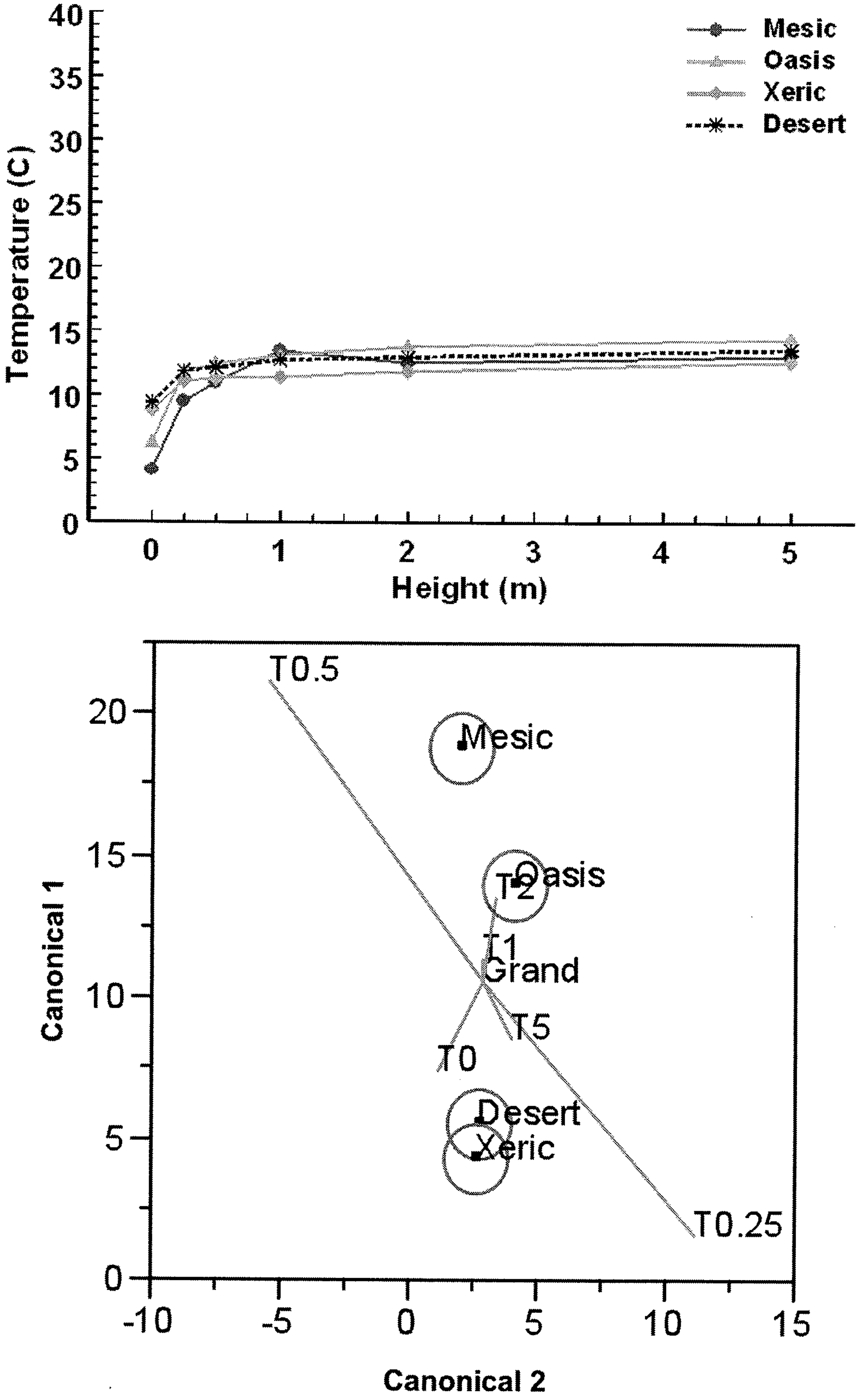
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Previous research examining the relationship between surface and air temperatures have utilized a combination of remote sensing, fixed meteorological stations or automobile-mounted transects (Gallo and Owen 1999, Hafner and Kidder, 1999, Stoll and Brazel 1992). In contrast, this study captured a more complete temperature profile through the under canopy layer. The major finding of this research indicated that neighborhoods landscaped with portions of irrigated turf had air temperatures that were noticeably cooler at near surface elevations.

The annual mean evapotranspiration in the Phoenix area is 1,843 mm of water. In contrast, the annual mean precipitation is 147 mm of water (The Arizona Meteorological Network, 2010). As a result, supplemental irrigation is required in the Phoenix area to maintain most residential landscapes. Efforts to reduce the amount of supplemental irrigation necessary have lead to a wide variety of landscape designs, including a diversity of low water-use plant taxa, planting densities and inorganic surface mulch cover types.

The effect of turfgrass as a landscape surface cover in the mesic and oasis treatments, during pre-monsoon summer conditions, which are hot and dry, was to reduce air temperature at elevations up to approximately 2.0 meters. This effect was most pronounced during the middle of the day, due to latent heat transfer from evaporative cooling. The vertical range of the influence observed in the mesic and oasis treatment was less than the 5.0 m originally hypothesized.

The turfgrass in the mesic treatment received 222.6 l/m^2/month supplemental water as irrigation during pre-monsoon conditions. During the same time period, the turfgrass-covered portion of the oasis treatment received approximately 458.3 l/m^2/month. The difference in irrigation rates was a result of differences in the precipitation rates of the different sprinkler types used to irrigate the turfgrass in the two treatments. The sprinkler heads in the mesic treatment were solely stream rotor heads, while the sprinkler heads in the oasis treatment were both stream rotor heads in the common areas and conventional overhead spray heads around in the turf areas near the houses. Spray heads

delivered water at a much higher rate, which explains the difference in irrigation rates between the mesic and oasis treatment.

During monsoon summer conditions, which were hot and more humid than pre-monsoon conditions, the effect of turfgrass as a surface cover in the mesic and oasis treatments displayed a similar, but less pronounced pattern on air temperature cooling. These results supported the hypothesis that microclimate effects as a result of landscape design would be decreased during monsoon conditions.

In comparison to pre-monsoon irrigation rates, the turfgrass in the mesic treatment received 281.7 l/m^2 during monsoon conditions and the turfgrass portion of the oasis treatment was irrigated at a rate of 392.2 l/m^2. Although irrigation rates were similar in pre-monsoon and monsoon conditions, increased atmospheric humidity suppressed the capacity for evaporative cooling in the landscape which resulted in reduced air temperatures in the treatments with turfgrass at elevations up to approximately one meter. Spronken-Smith and Oke (1998) found evaporative cooling in parks to have a greater effect on air temperatures in Sacramento, California than in Vancouver, British Columbia. Relative humidities were not reported, but Spronken-Smith et al. (2000) describe Sacramento's climate as "hot and dry", much like pre-monsoon conditions in Phoenix. It is not unreasonable to assume relative humidity to be a contributing factor in limiting the evaporative cooling potential of turfed areas.

For the most part, there was very little difference in relative humidity (2 m height) across the treatments, regardless of season. The two exceptions are during the monsoon night collection period in the desert treatment, and the winter night collection period in the oasis treatment. The higher humidity in the desert treatment during the monsoon night collection period is due to the large irrigation event that was occurring before and during the data collection period at an adjacent golf course. The lower humidity in the oasis treatment during the winter night collection period is the result of natural variation in synoptic weather conditions.

The evaportranspiration (ETo) during the winter data collection was 14.5 mm. In comparison, the pre-monsoon ETo was 40.4 mm and monsoon ETo was 142.2 mm. Irrigation was determined by daily ETo rates and as a result, irrigation during the winter collection period was minimal. Limited water additions to the landscape in connection with less incoming solar radiation meant there was very little evaportanspirational cooling in the treatments during the winter. Spronken-Smith et al. (2000) suggest turfed park areas act like large, wet leaves in "thermostating" surrounding air temperatures, such that during peak heat input, temperatures of irrigated surfaces may be much lower than the air above it. The temperature profiles show that irrigated treatments had much lower surface temperatures than the synoptic air temperatures and un-irrigated treatments have surface temperatures that are much higher than the synoptic air temperatures.

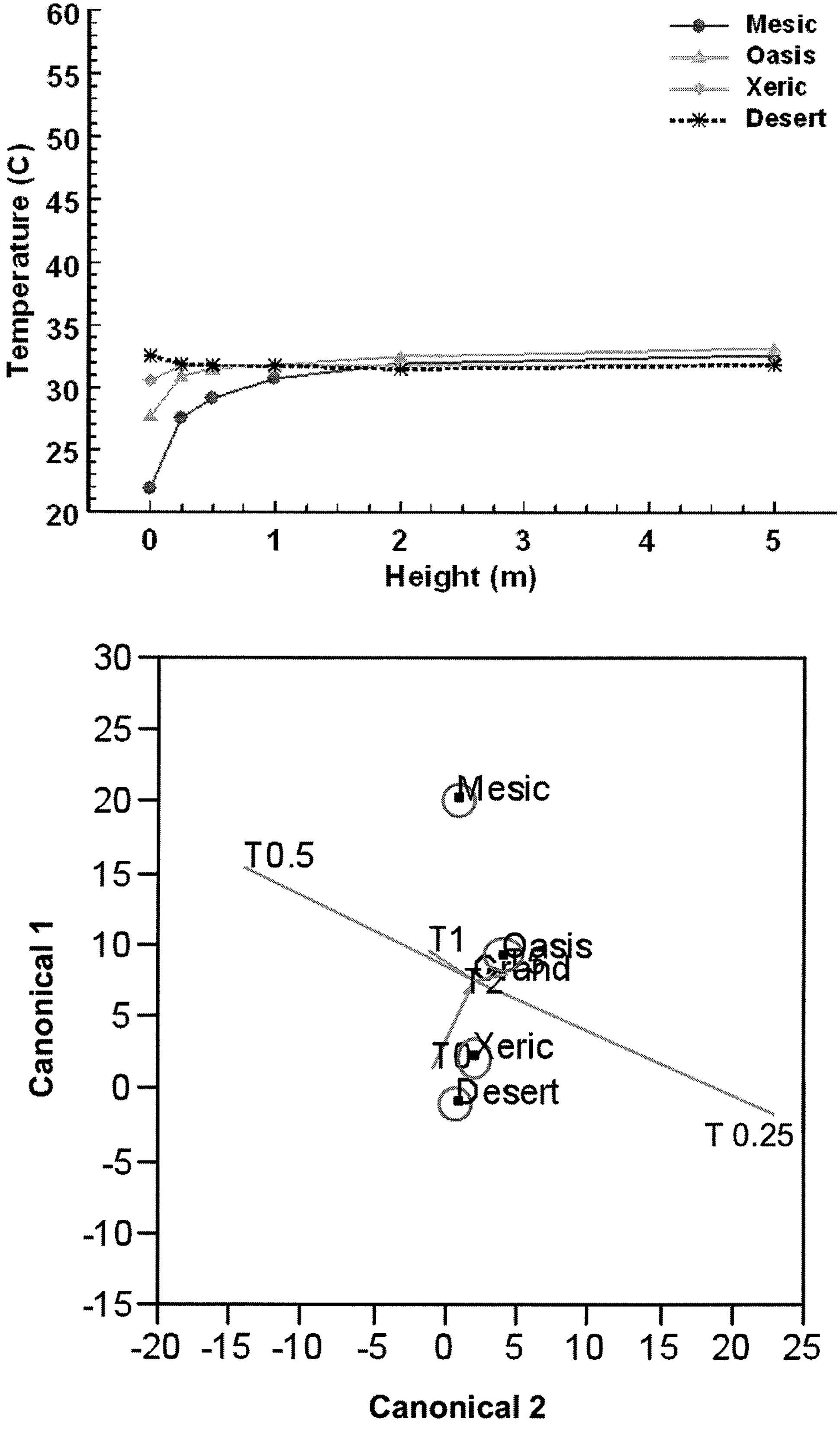
The results of this study indicate that for residential neighborhoods, the strategic use of turfgrass will provide the benefit of heat mitigation in the region of human activity during the summer months, especially during the hot and dry conditions that dominate Arizona summers. However, unoverseeded landscapes will not impact air temperatures during winter, when heat mitigation is not desirable. Homeowners who wish to maximize the heat mitigation utility of their landscapes but limit water consumption should plant judicious amounts of summer lawns in areas of high human activity. Spronken-Smith and Oke (1998) found that the horizontal influence of parks on air temperature extended into the surrounding area approximately the same width of the park. Results of this study indicate that in the Phoenix climate, surface cover is the dominant influence on near-surface air temperatures. However, since widespread turf, such as found in the mesic treatment, is impractical in the current culture which promotes water conservation, it is desirable to create residential landscape designs that maximize heat mitigation while limiting water consumption. Consequently, more research on the widespread effect of different size turf fragments would provide insights useful for residential landscape designers.

Additionally, this research was conducted on immature landscapes. At the time of data collection, the treatments were only three years old. As a result, shade from the small, young trees did not have a noticeable impact on surface or air temperatures. Research which incorporates the effect of mature shade trees

on microclimates in the Phoenix region will allow for even better landscape design recommendations.

Because this research utilized air temperatures throughout the vertical profile, it will be useful to connect in situ temperatures with data collected through remote sensing. Doing so will enable the creation of better, more accurate models for explaining and predicting the UHI. Current mesoscale models, such as WRF (Weather Research and Forcasting, 2010), are commonly used to predict weather in cities and across regions but are unable to capture fine scale differences within urban settings (The Weather Research & Forecasting Model, 2010). The data presented in this study provide the fine scale resolution in temperature patterns that occur because of differences in landscape design at the neighborhood scale.

Figure 5c.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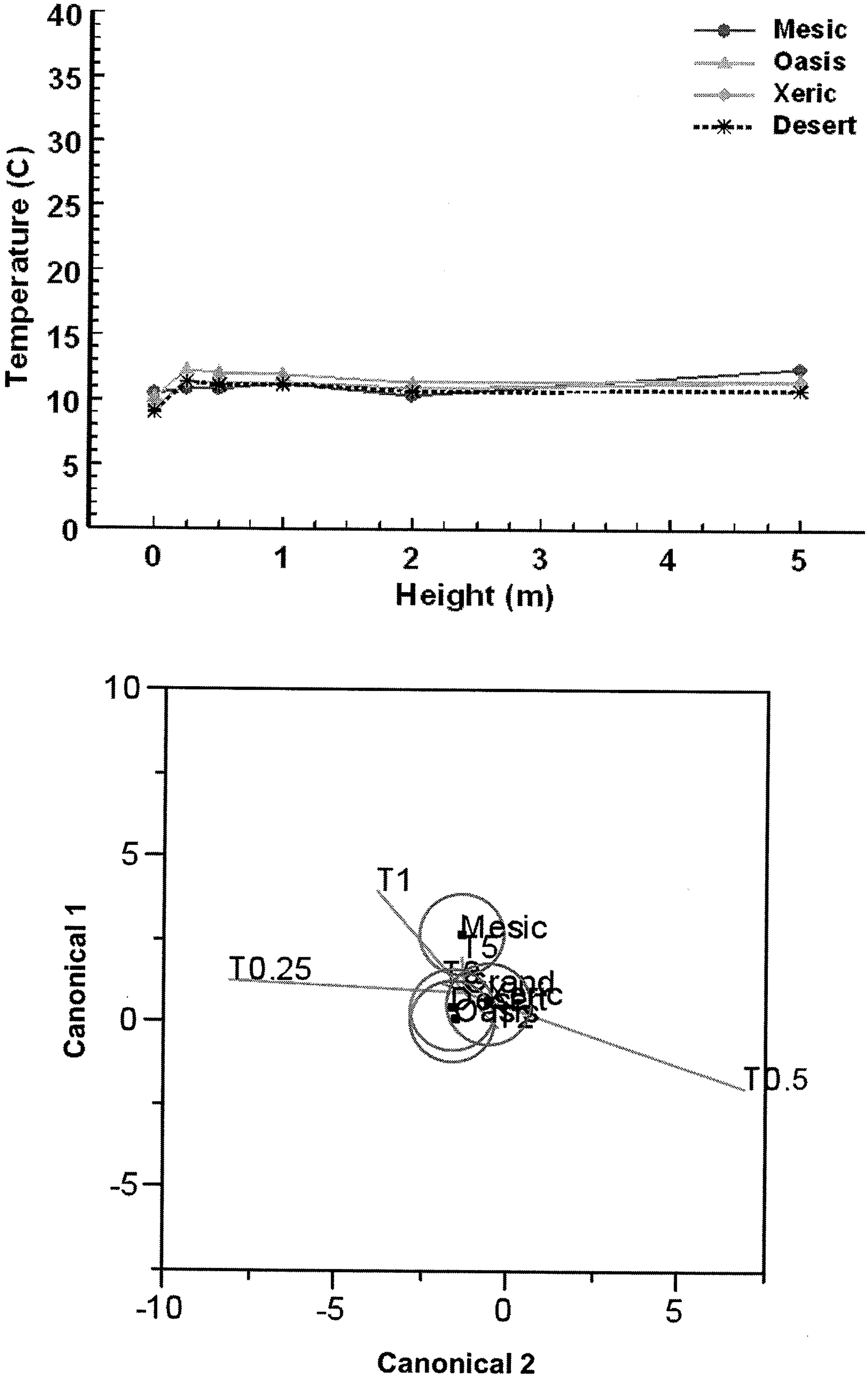
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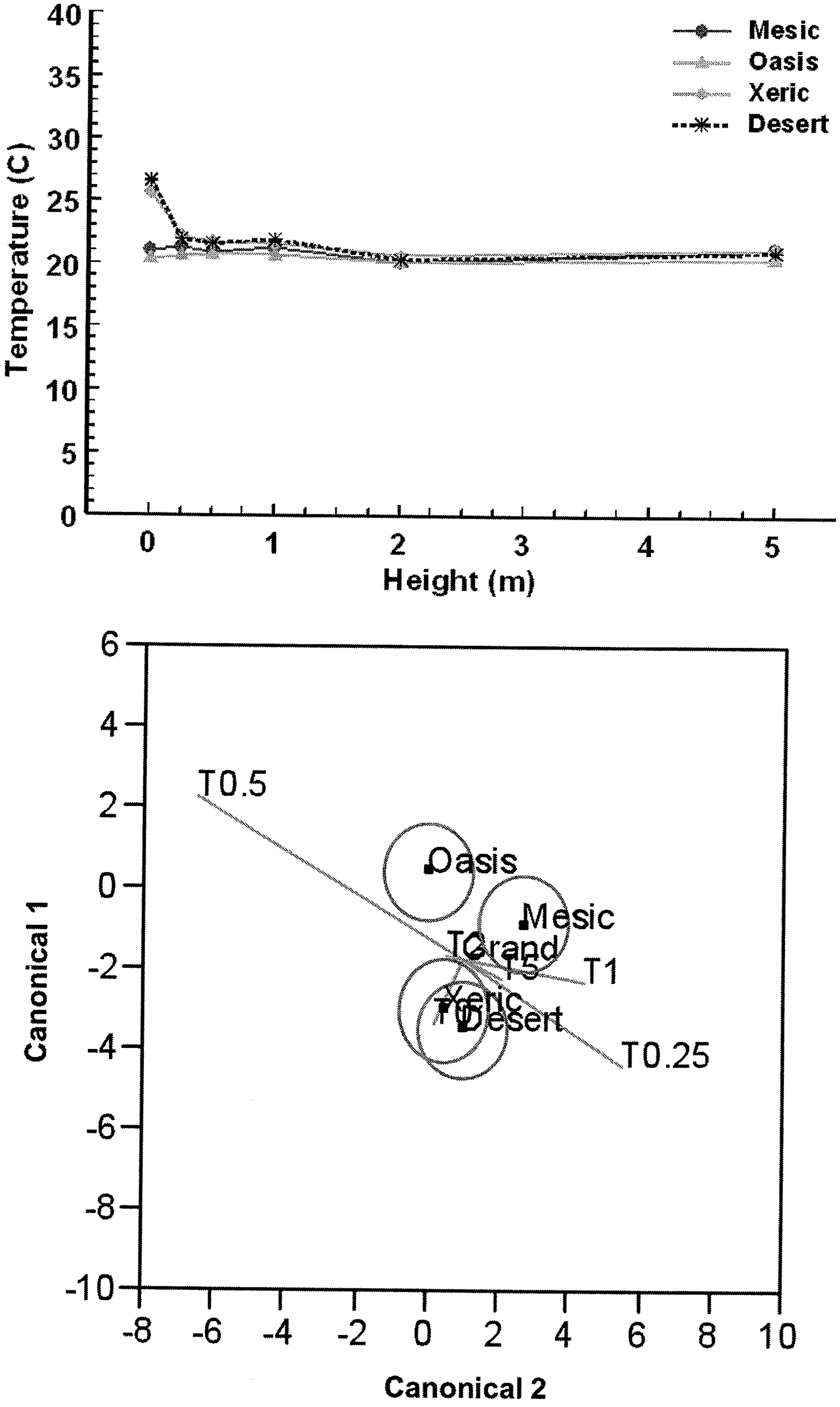
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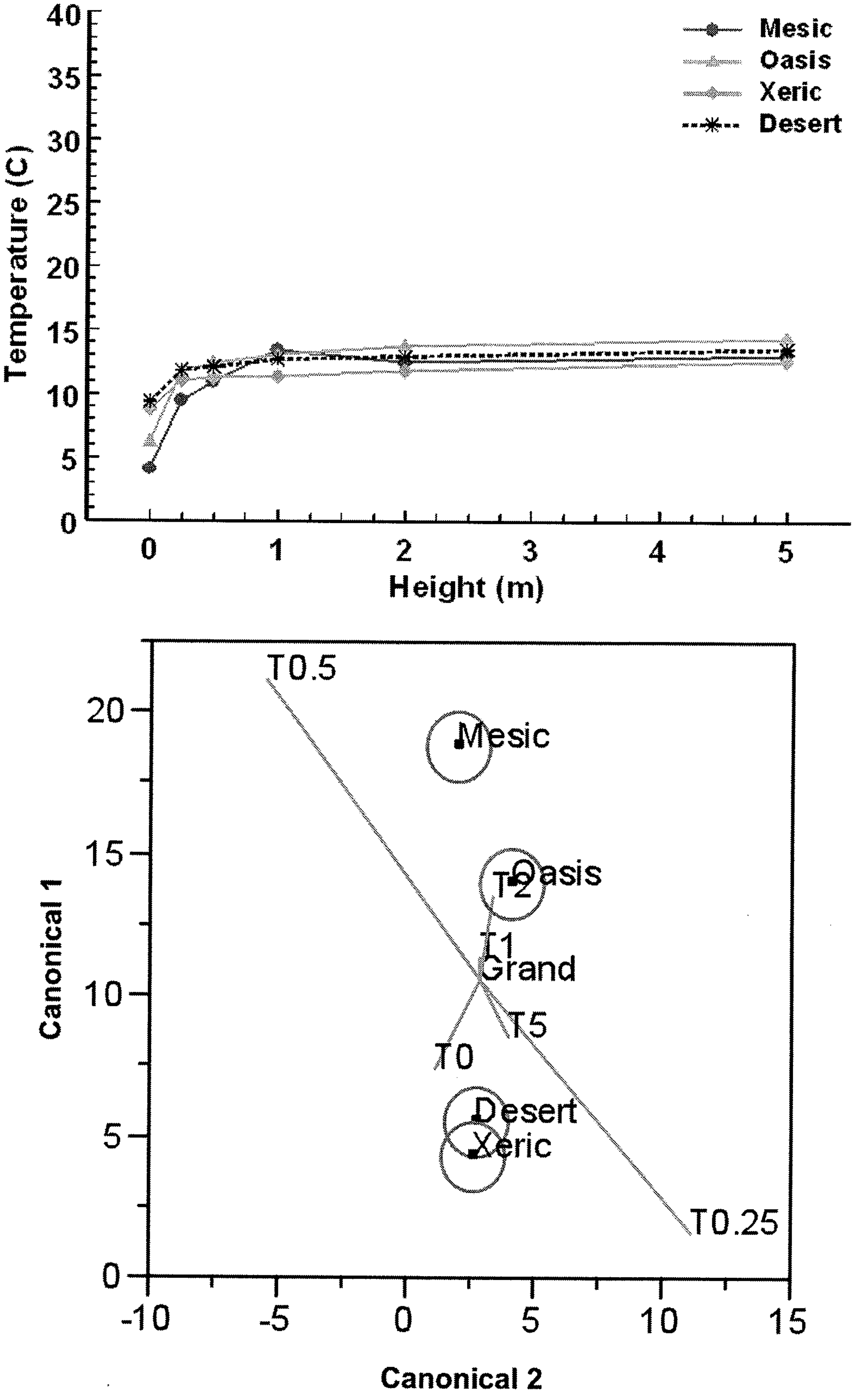

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In comparison to pre-monsoon irrigation rates, the turfgrass in the mesic treatment received 281.7 l/m^2 during monsoon conditions and the turfgrass portion of the oasis treatment was irrigated at a rate of 392.2 l/m^2. Although irrigation rates were similar in pre-monsoon and monsoon conditions, increased atmospheric humidity suppressed the capacity for evaporative cooling in the landscape which resulted in reduced air temperatures in the treatments with turfgrass at elevations up to approximately one meter. Spronken-Smith and Oke (1998) found evaporative cooling in parks to have a greater effect on air temperatures in Sacramento, California than in Vancouver, British Columbia. Relative humidities were not reported, but Spronken-Smith et al. (2000) describe Sacramento's climate as "hot and dry", much like pre-monsoon conditions in Phoenix. It is not unreasonable to assume relative humidity to be a contributing factor in limiting the evaporative cooling potential of turfed areas.

For the most part, there was very little difference in relative humidity (2 m height) across the treatments, regardless of season. The two exceptions are during the monsoon night collection period in the desert treatment, and the winter night collection period in the oasis treatment. The higher humidity in the desert treatment during the monsoon night collection period is due to the large irrigation event that was occurring before and during the data collection period at an adjacent golf course. The lower humidity in the oasis treatment during the winter night collection period is the result of natural variation in synoptic weather conditions.

The evaportranspiration (ETo) during the winter data collection was 14.5 mm. In comparison, the pre-monsoon ETo was 40.4 mm and monsoon ETo was 142.2 mm. Irrigation was determined by daily ETo rates and as a result, irrigation during the winter collection period was minimal. Limited water additions to the landscape in connection with less incoming solar radiation meant there was very little evaportanspirational cooling in the treatments during the winter. Spronken-Smith et al. (2000) suggest turfed park areas act like large, wet leaves in "thermostating" surrounding air temperatures, such that during peak heat input, temperatures of irrigated surfaces may be much lower than the air above it. The temperature profiles show that irrigated treatments had much lower surface temperatures than the synoptic air temperatures and un-irrigated treatments have surface temperatures that are much higher than the synoptic air temperatures.

The results of this study indicate that for residential neighborhoods, the strategic use of turfgrass will provide the benefit of heat mitigation in the region of human activity during the summer months, especially during the hot and dry conditions that dominate Arizona summers. However, unoverseeded landscapes will not impact air temperatures during winter, when heat mitigation is not desirable. Homeowners who wish to maximize the heat mitigation utility of their landscapes but limit water consumption should plant judicious amounts of summer lawns in areas of high human activity. Spronken-Smith and Oke (1998) found that the horizontal influence of parks on air temperature extended into the surrounding area approximately the same width of the park. Results of this study indicate that in the Phoenix climate, surface cover is the dominant influence on near-surface air temperatures. However, since widespread turf, such as found in the mesic treatment, is impractical in the current culture which promotes water conservation, it is desirable to create residential landscape designs that maximize heat mitigation while limiting water consumption. Consequently, more research on the widespread effect of different size turf fragments would provide insights useful for residential landscape designers.

Additionally, this research was conducted on immature landscapes. At the time of data collection, the treatments were only three years old. As a result, shade from the small, young trees did not have a noticeable impact on surface or air temperatures. Research which incorporates the effect of mature shade trees

on microclimates in the Phoenix region will allow for even better landscape design recommendations.

Because this research utilized air temperatures throughout the vertical profile, it will be useful to connect in situ temperatures with data collected through remote sensing. Doing so will enable the creation of better, more accurate models for explaining and predicting the UHI. Current mesoscale models, such as WRF (Weather Research and Forcasting, 2010), are commonly used to predict weather in cities and across regions but are unable to capture fine scale differences within urban settings (The Weather Research & Forecasting Model, 2010). The data presented in this study provide the fine scale resolution in temperature patterns that occur because of differences in landscape design at the neighborhood scale.

Figure 5c.

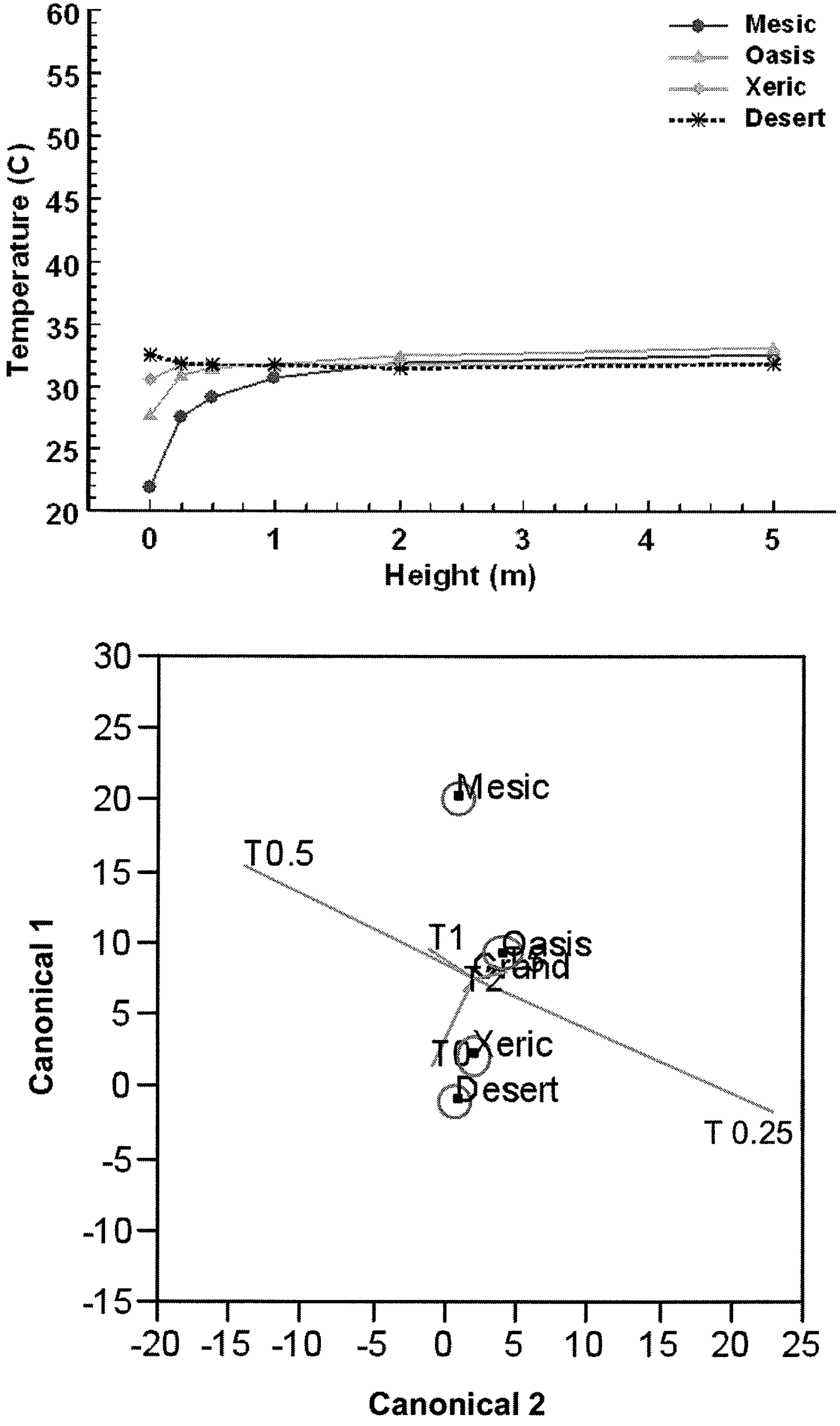
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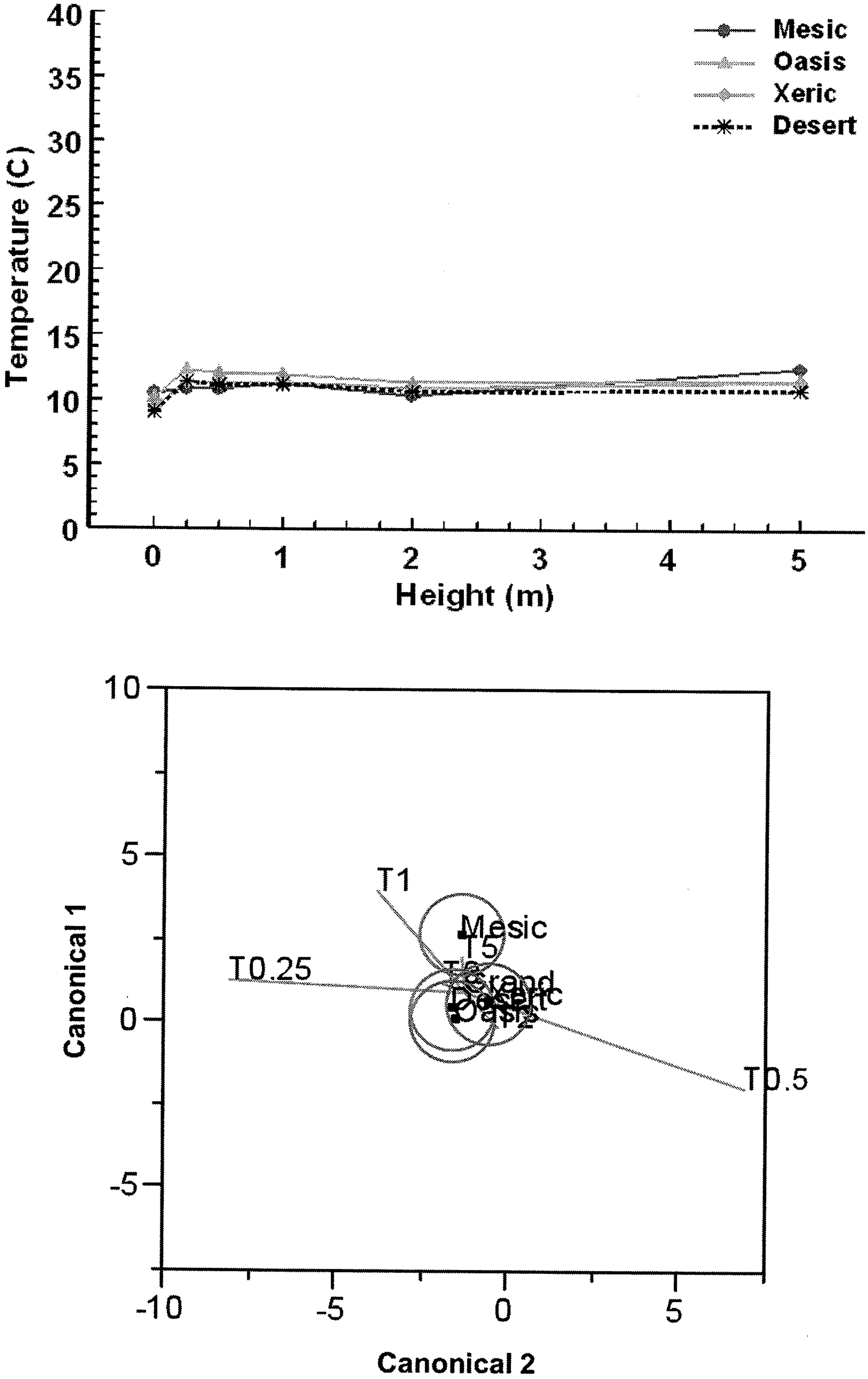
Figure 5c. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during monsoon 2007 evening (2100 to 2200 Hr) in response to four landscape design treatments. Treatments include: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

Below: Canonical correlation analysis. Canonical circles show the 95% confidence intervals around the distribution centroid of each landscape design treatment. Overlapping centriods indicate that those treatments are not significantly different from each other. Biplot rays, originating from the grand mean show directions of relative responsiveness in canonical space. (T0=surface, T.025=0.25 m, T.05=0.5 m, T1=1.0 m, T2=2.0 m, T5=5.0 m).

detected for the 0.25-m and 0.5-m heights (Fig. 5c). Mean relative humidities and saturation vapor pressures across treatments during the monsoon evenings ranged from 24.3% (mesic) to 44.9% (desert) and 4.40 to 5.50 KPa, respectively (Table 4).

Winter 2008. Repeated measures analyses of the data showed differences by time of day in the way landscape design treatments affected temperature height profiles (Fig. 6a-c). For mornings, the temperature height profiles of all four landscape design treatments were visually similar (Fig. 6a) — as indicated by slightly lower adjusted mean temperatures on the surface and then a relatively constant adjusted mean temperature over a small range between 0.25-m to 5.0-m heights. In fact, treatment-related differences in the winter morning adjusted mean temperatures were 2°C or less at all heights. Canonical centroid plots and test contrasts between the treatments showed distinct pairings of desert and xeric treatments (G-G Epsilon P=0.8017), desert and oasis treatments (G-G Epsilon P=0.8871), and xeric and oasis treatments (G-G Epsilon P=0.6648). Even though the mesic treatment profile was statistically significantly different from the clustered group of desert, xeric, and oasis treatment profiles (G-G Epsilon P=0.0137), a visual assessment of the data does not reflect this. For winter mornings, strong dissimilarities in the direction of biplot rays within canonical space were detected between the 0.5-m and the 0.25-m and 1 m heights (Fig. 6a). Across all treatments, mean relative humidities and saturation vapor pressures ranged from 59.9% (mesic) to 70.6% (xeric) and 1.05 to 1.48 KPa, respectively (Table 4).

Figure 6a.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For winter afternoon, temperature height profiles were affected by landscape design treatment most extensively at the landscape surface, but to a lesser extent than was found during the afternoon hours during either pre-monsoon or monsoon 2007 (Fig. 6b). Canonical centroid plots and test contrasts between the treatments showed a distinct pairing of desert and xeric treatment temperature height profiles (G-G Epsilon P=0.5291) that were both different from the oasis or mesic profiles (G-G Epsilon P=0.0001). Moreoever, the mesic and oasis temperature height profiles also showed a distinct pairing (G-G Epsilon P=0.8360). The greatest difference in mean adjusted temperatures (6°C) was recorded at the landscape surface between the desert (27°C) and oasis (21°C) treatments. In contrast, treatment-related differences in mean adjusted temperatures at the 2-m and 5-m heights were 1°C or less. For winter afternoons, strong dissimilarities within canonical space in the direction of biplot rays were detected for the 0.25-m and the 0.5-m heights (Fig. 6b). Mean relative humidities and saturation vapor pressures across all treatments during the afternoon ranged from 25.3% (oasis) to 35.2% (xeric) and 1.78 to 2.70 KPa, respectively (Table 4).

For winter evenings, the temperature height profiles of all treatments exhibited certain trends toward decreased temperatures close too and at the surface that were related to the the extent of turf grass cover (Fig. 6c). Canonical centroid plots and test contrasts between the treatments showed a distinct pairing of desert and xeric treatment temperature height profiles (G-G Epsilon

Figure 6b.

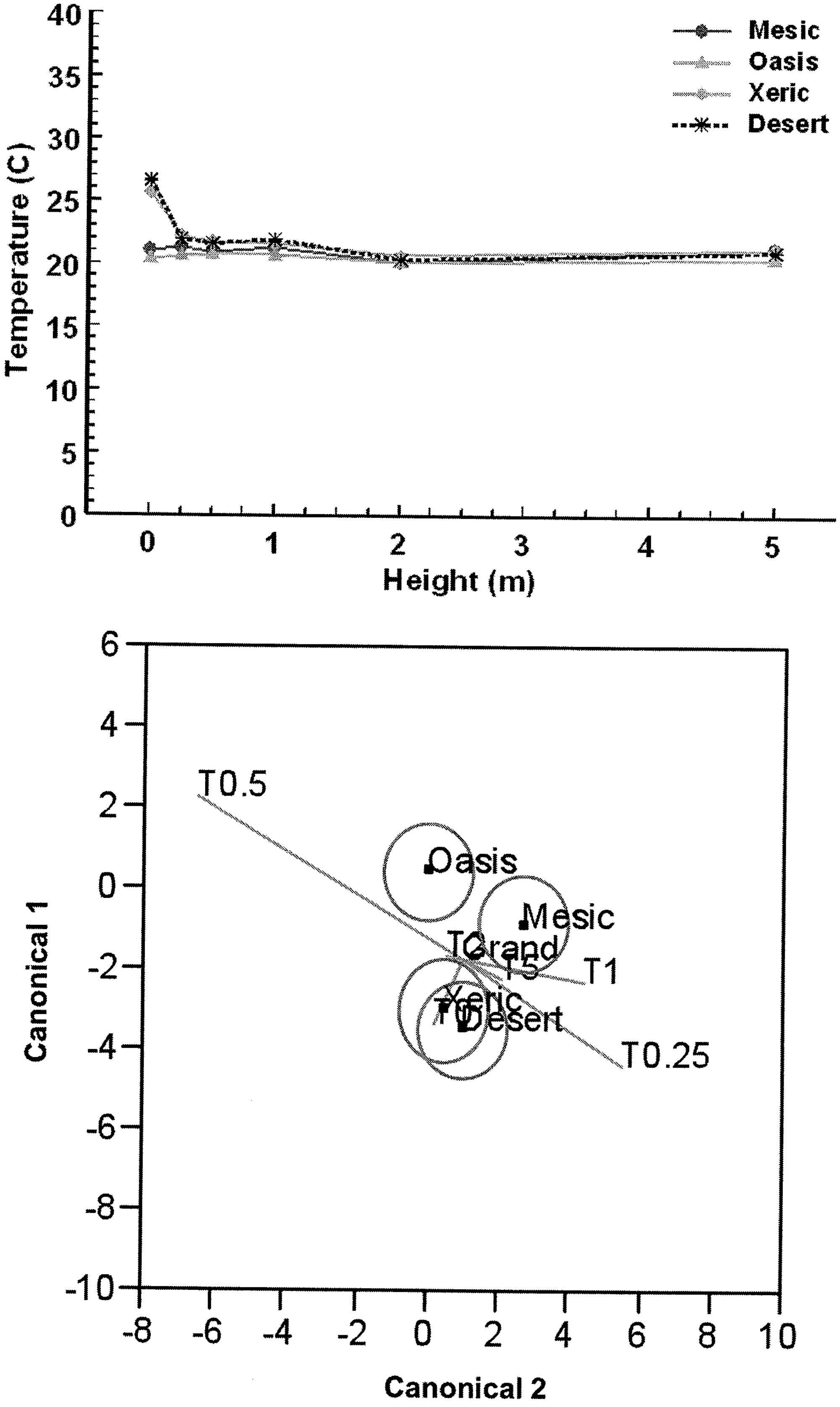
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Figure 6b. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during winter 2008 afternoon (1600 to 1700 Hr) in response to four landscape design treatments. Treatments include: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

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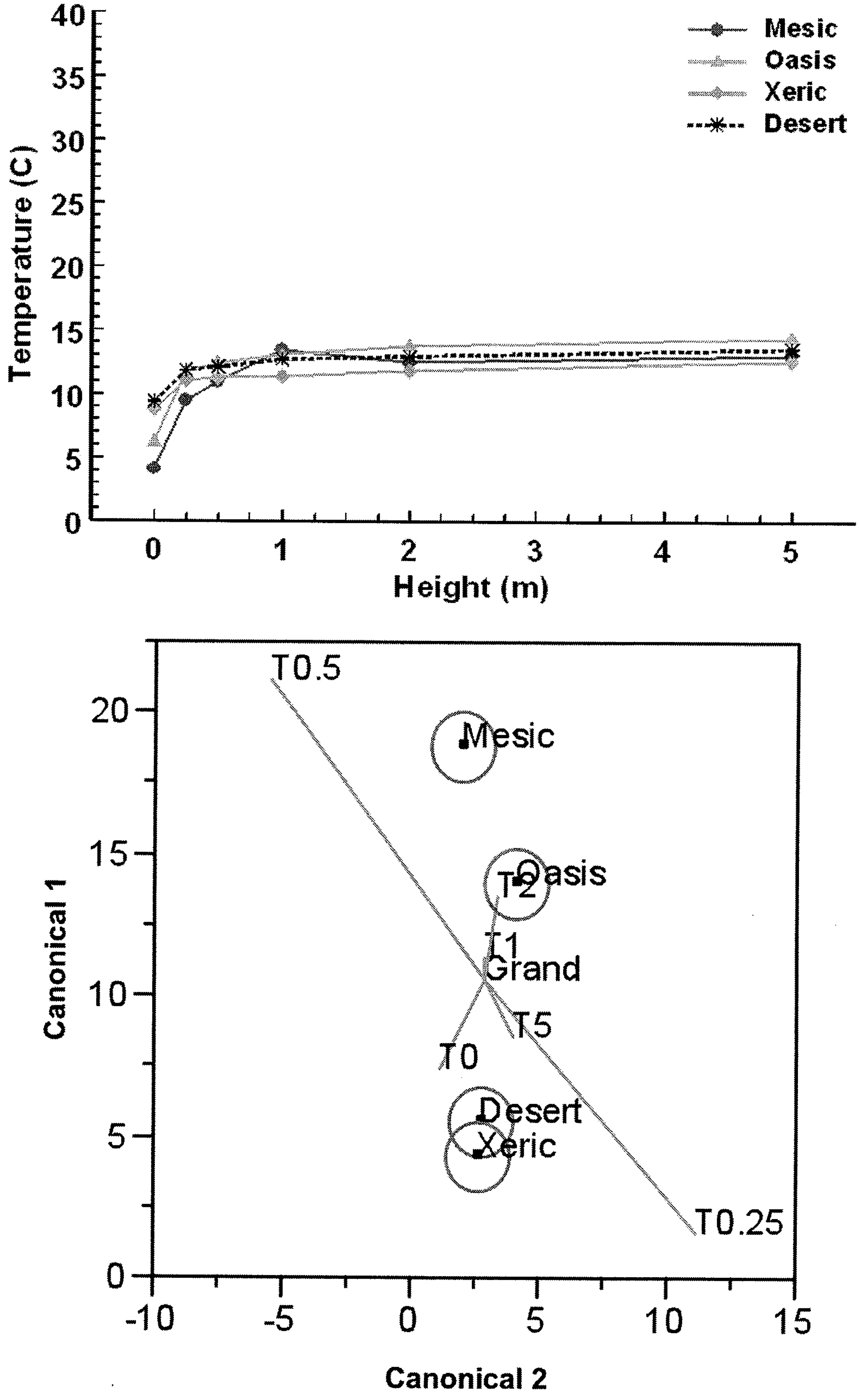
Figure 6c.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P=0.7768) that were both significantly different from the oasis or mesic profiles (G-G Epsilon P=0.0001). Additionally, the mesic and oasis temperature height profiles showed moderate similarity (G-G Epsilon P=0.1081). The greatest differences in mean adjusted temperatures (5°C) occurred at the landscape surface and were recorded between the desert (9°C) and mesic (4°C) treatments. In contrast, treatment-related differences in mean adjusted air temperature between 1 m and 5 m were only about 3°C. Similar to winter afternoons, strong dissimilarities in the direction of biplot rays within canonical space were detected for winter evenings at the 0.25-m and the 0.5-m heights (Fig. 6c). Across all treatments, mean relative humidities and saturation vapor pressures ranged from 41.8% (oasis) to 70.1% (xeric) and 1.22 to 1.74 KPa, respectively (Table 4).

Chapter 4

Discussion And Conclusions

Residential landscape designs found in the Phoenix metropolitan area vary across a gradient of water usage, which influences plant selection, plant placement and overall style of the landscape. The four design styles utilized in this research represent four archetypes along that gradient. Understanding the relationship between the landscape design style and its affect on the immediately surrounding air temperatures will lead to more informed decisions about landscape design in the area. The purpose of this research was to determine the extent to which landscape design style affects vertical air temperatures at the neighborhood scale across three seasons. This research was conducted during pre-monsoon and monsoon conditions of 2007 and winter 2008 on days that had clear, calm anticylonic synoptic weather conditions.

Previous research examining the relationship between surface and air temperatures have utilized a combination of remote sensing, fixed meteorological stations or automobile-mounted transects (Gallo and Owen 1999, Hafner and Kidder, 1999, Stoll and Brazel 1992). In contrast, this study captured a more complete temperature profile through the under canopy layer. The major finding of this research indicated that neighborhoods landscaped with portions of irrigated turf had air temperatures that were noticeably cooler at near surface elevations.

The annual mean evapotranspiration in the Phoenix area is 1,843 mm of water. In contrast, the annual mean precipitation is 147 mm of water (The Arizona Meteorological Network, 2010). As a result, supplemental irrigation is required in the Phoenix area to maintain most residential landscapes. Efforts to reduce the amount of supplemental irrigation necessary have lead to a wide variety of landscape designs, including a diversity of low water-use plant taxa, planting densities and inorganic surface mulch cover types.

The effect of turfgrass as a landscape surface cover in the mesic and oasis treatments, during pre-monsoon summer conditions, which are hot and dry, was to reduce air temperature at elevations up to approximately 2.0 meters. This effect was most pronounced during the middle of the day, due to latent heat transfer from evaporative cooling. The vertical range of the influence observed in the mesic and oasis treatment was less than the 5.0 m originally hypothesized.

The turfgrass in the mesic treatment received 222.6 $l/m^2/month$ supplemental water as irrigation during pre-monsoon conditions. During the same time period, the turfgrass-covered portion of the oasis treatment received approximately 458.3 $l/m^2/month$. The difference in irrigation rates was a result of differences in the precipitation rates of the different sprinkler types used to irrigate the turfgrass in the two treatments. The sprinkler heads in the mesic treatment were solely stream rotor heads, while the sprinkler heads in the oasis treatment were both stream rotor heads in the common areas and conventional overhead spray heads around in the turf areas near the houses. Spray heads

delivered water at a much higher rate, which explains the difference in irrigation rates between the mesic and oasis treatment.

During monsoon summer conditions, which were hot and more humid than pre-monsoon conditions, the effect of turfgrass as a surface cover in the mesic and oasis treatments displayed a similar, but less pronounced pattern on air temperature cooling. These results supported the hypothesis that microclimate effects as a result of landscape design would be decreased during monsoon conditions.

In comparison to pre-monsoon irrigation rates, the turfgrass in the mesic treatment received 281.7 l/m^2 during monsoon conditions and the turfgrass portion of the oasis treatment was irrigated at a rate of 392.2 l/m^2. Although irrigation rates were similar in pre-monsoon and monsoon conditions, increased atmospheric humidity suppressed the capacity for evaporative cooling in the landscape which resulted in reduced air temperatures in the treatments with turfgrass at elevations up to approximately one meter. Spronken-Smith and Oke (1998) found evaporative cooling in parks to have a greater effect on air temperatures in Sacramento, California than in Vancouver, British Columbia. Relative humidities were not reported, but Spronken-Smith et al. (2000) describe Sacramento's climate as “hot and dry”, much like pre-monsoon conditions in Phoenix. It is not unreasonable to assume relative humidity to be a contributing factor in limiting the evaporative cooling potential of turfed areas.

For the most part, there was very little difference in relative humidity (2 m height) across the treatments, regardless of season. The two exceptions are during the monsoon night collection period in the desert treatment, and the winter night collection period in the oasis treatment. The higher humidity in the desert treatment during the monsoon night collection period is due to the large irrigation event that was occurring before and during the data collection period at an adjacent golf course. The lower humidity in the oasis treatment during the winter night collection period is the result of natural variation in synoptic weather conditions.

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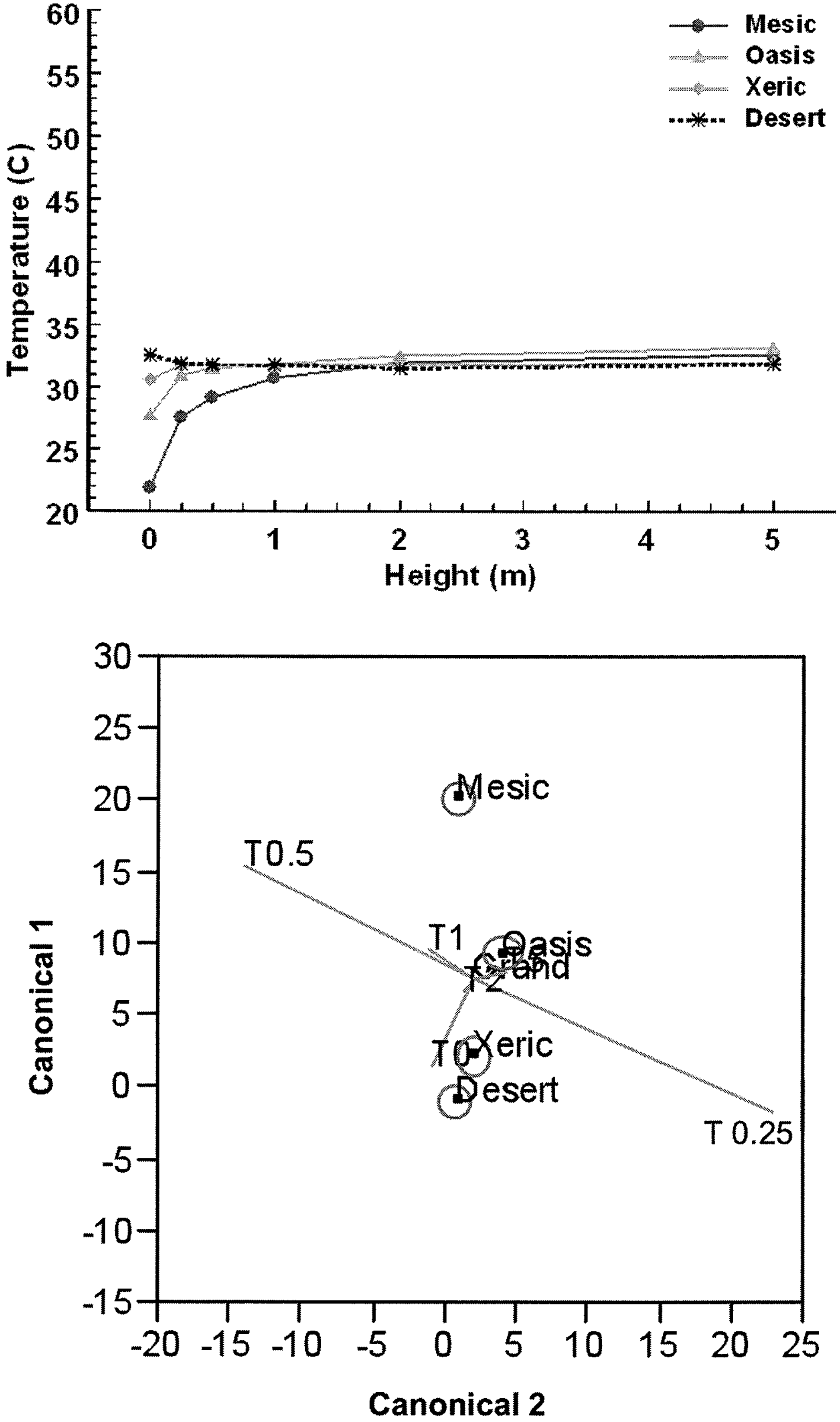
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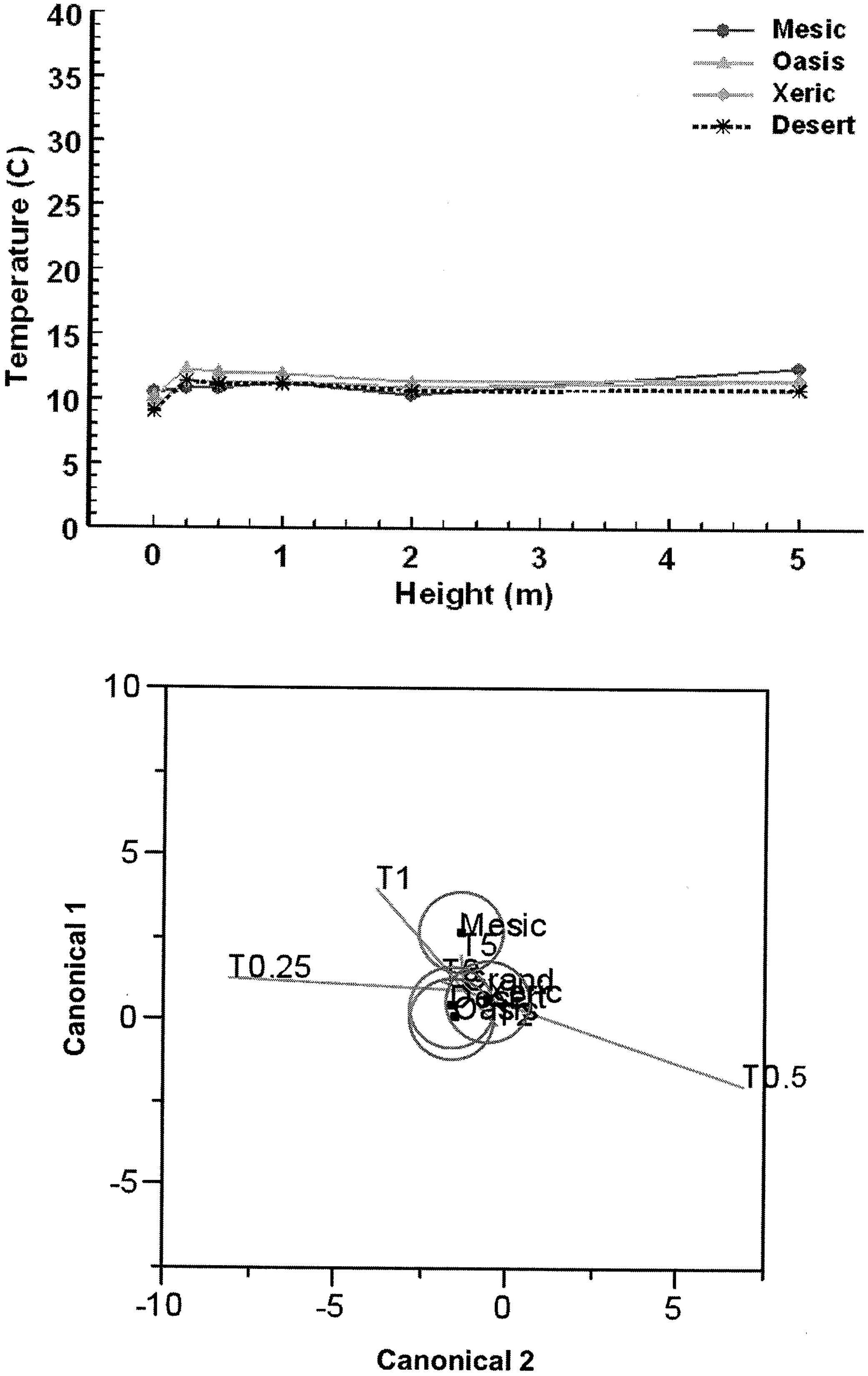
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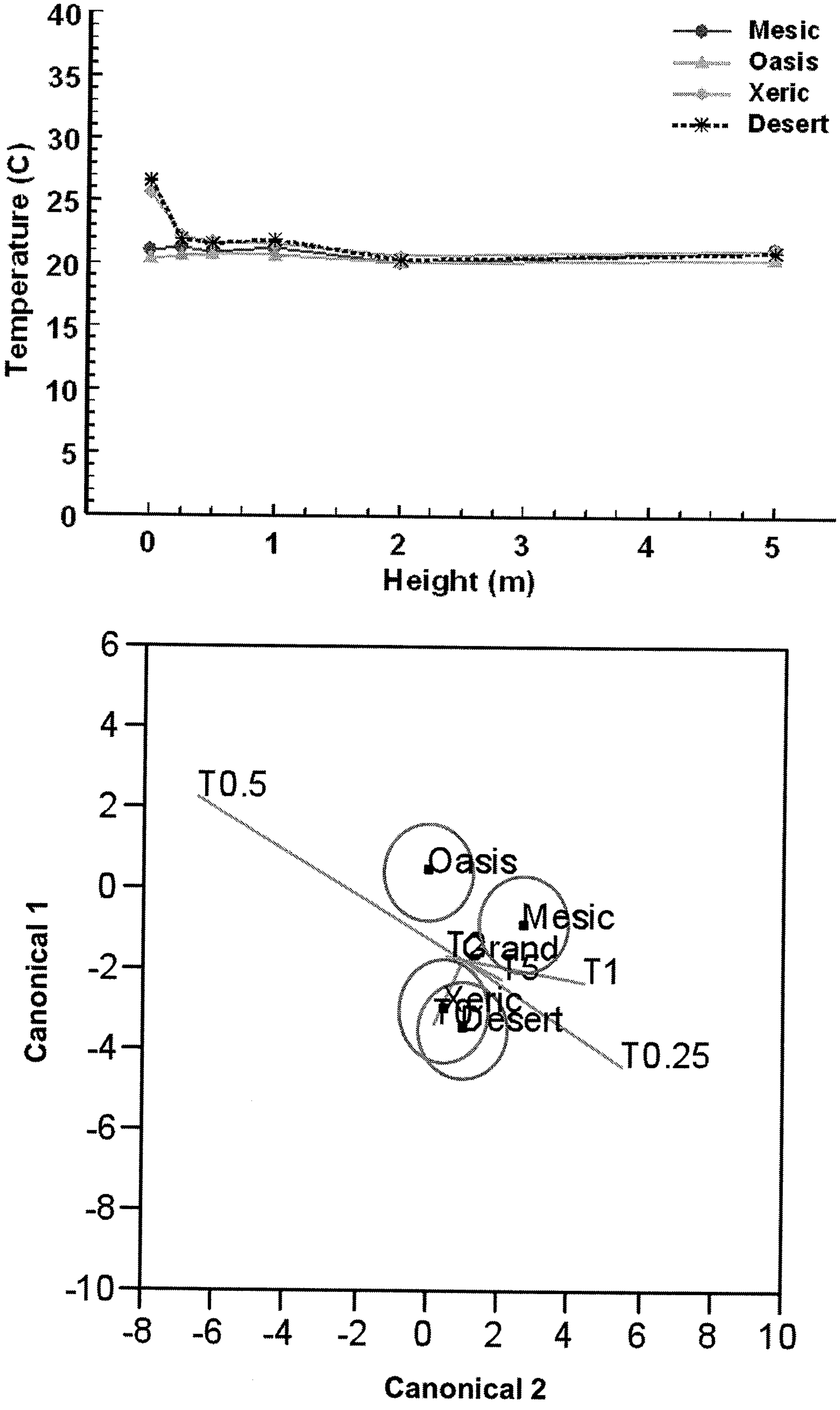
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T0.25

Figure 6b. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during winter 2008 afternoon (1600 to 1700 Hr) in response to four landscape design treatments. Treatments include: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

Below: Canonical correlation analysis. Canonical circles show the 95% confidence intervals around the distribution centroid of each landscape design treatment. Overlapping centriods indicate that those treatments are not significantly different from each other. Biplot rays, originating from the grand mean show directions of relative responsiveness in canonical space. (T0=surface, T.025=0.25 m, T.05=0.5 m, T1=1.0 m, T2=2.0 m, T5=5.0 m).

Figure 6c.

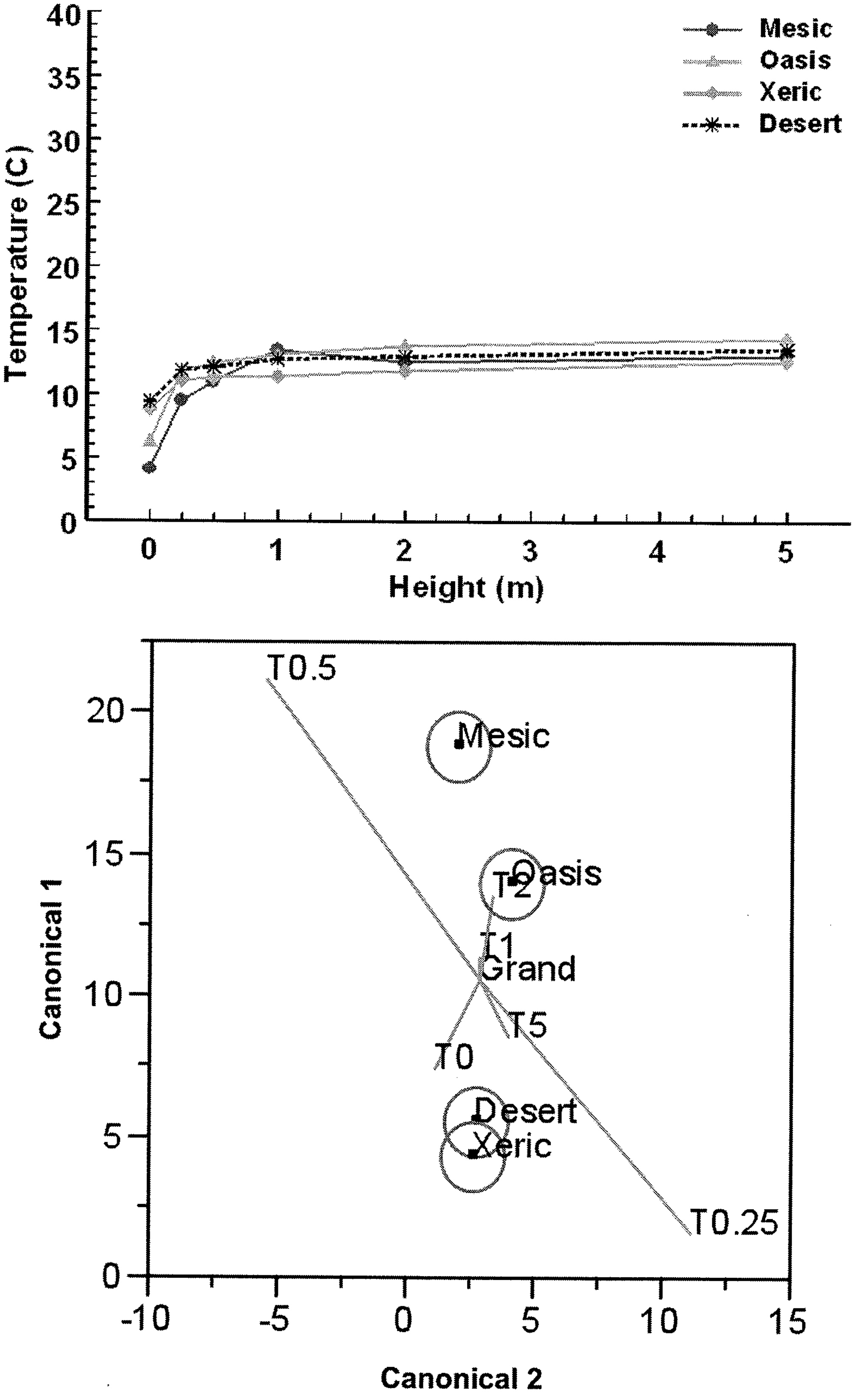
Mesic
Oasis
Xeric
Desert
Temperature (C)
0
5
10
15
20
25
30
35
40
Height (m)
0
1
2
3
4
5
T0.5
Mesic
Oasis
T2
T1
Grand
T5
T0
Desert
Xeric
T0.25
Canonical 1
0
5
10
15
20
Canonical 2
-10
-5
0
5
10
15

Figure 6c. Above: Adjusted mean temperature profiles (0.0 to 5.0 m above ground) during winter 2008 evening (2100 to 2200 Hr) in response to four landscape design treatments. Treatments include: Mesic (sprinkler irrigation, turf, trees); Oasis (sprinkler and drip irrigation, turf, trees and shrubs, decomposing granite mulch); Xeric (drip irrigation, trees and shrubs, decomposing granite mulch); and Desert (no irrigation, trees and shrubs, decomposing granite mulch).

Below: Canonical correlation analysis. Canonical circles show the 95% confidence intervals around the distribution centroid of each landscape design treatment. Overlapping centriods indicate that those treatments are not significantly different from each other. Biplot rays, originating from the grand mean show directions of relative responsiveness in canonical space. (T0=surface, T.025=0.25 m, T.05=0.5 m, T1=1.0 m, T2=2.0 m, T5=5.0 m).

P=0.7768) that were both significantly different from the oasis or mesic profiles (G-G Epsilon P=0.0001). Additionally, the mesic and oasis temperature height profiles showed moderate similarity (G-G Epsilon P=0.1081). The greatest differences in mean adjusted temperatures (5°C) occurred at the landscape surface and were recorded between the desert (9°C) and mesic (4°C) treatments. In contrast, treatment-related differences in mean adjusted air temperature between 1 m and 5 m were only about 3°C. Similar to winter afternoons, strong dissimilarities in the direction of biplot rays within canonical space were detected for winter evenings at the 0.25-m and the 0.5-m heights (Fig. 6c). Across all treatments, mean relative humidities and saturation vapor pressures ranged from 41.8% (oasis) to 70.1% (xeric) and 1.22 to 1.74 KPa, respectively (Table 4).

Chapter 4

Discussion And Conclusions

Residential landscape designs found in the Phoenix metropolitan area vary across a gradient of water usage, which influences plant selection, plant placement and overall style of the landscape. The four design styles utilized in this research represent four archetypes along that gradient. Understanding the relationship between the landscape design style and its affect on the immediately surrounding air temperatures will lead to more informed decisions about landscape design in the area. The purpose of this research was to determine the extent to which landscape design style affects vertical air temperatures at the neighborhood scale across three seasons. This research was conducted during pre-monsoon and monsoon conditions of 2007 and winter 2008 on days that had clear, calm anticylonic synoptic weather conditions.

Previous research examining the relationship between surface and air temperatures have utilized a combination of remote sensing, fixed meteorological stations or automobile-mounted transects (Gallo and Owen 1999, Hafner and Kidder, 1999, Stoll and Brazel 1992). In contrast, this study captured a more complete temperature profile through the under canopy layer. The major finding of this research indicated that neighborhoods landscaped with portions of irrigated turf had air temperatures that were noticeably cooler at near surface elevations.

The annual mean evapotranspiration in the Phoenix area is 1,843 mm of water. In contrast, the annual mean precipitation is 147 mm of water (The Arizona Meteorological Network, 2010). As a result, supplemental irrigation is required in the Phoenix area to maintain most residential landscapes. Efforts to reduce the amount of supplemental irrigation necessary have lead to a wide variety of landscape designs, including a diversity of low water-use plant taxa, planting densities and inorganic surface mulch cover types.

The effect of turfgrass as a landscape surface cover in the mesic and oasis treatments, during pre-monsoon summer conditions, which are hot and dry, was to reduce air temperature at elevations up to approximately 2.0 meters. This effect was most pronounced during the middle of the day, due to latent heat transfer from evaporative cooling. The vertical range of the influence observed in the mesic and oasis treatment was less than the 5.0 m originally hypothesized.

The turfgrass in the mesic treatment received 222.6 l/m^2/month supplemental water as irrigation during pre-monsoon conditions. During the same time period, the turfgrass-covered portion of the oasis treatment received approximately 458.3 l/m^2/month. The difference in irrigation rates was a result of differences in the precipitation rates of the different sprinkler types used to irrigate the turfgrass in the two treatments. The sprinkler heads in the mesic treatment were solely stream rotor heads, while the sprinkler heads in the oasis treatment were both stream rotor heads in the common areas and conventional overhead spray heads around in the turf areas near the houses. Spray heads

delivered water at a much higher rate, which explains the difference in irrigation rates between the mesic and oasis treatment.

During monsoon summer conditions, which were hot and more humid than pre-monsoon conditions, the effect of turfgrass as a surface cover in the mesic and oasis treatments displayed a similar, but less pronounced pattern on air temperature cooling. These results supported the hypothesis that microclimate effects as a result of landscape design would be decreased during monsoon conditions.

In comparison to pre-monsoon irrigation rates, the turfgrass in the mesic treatment received 281.7 l/m^2 during monsoon conditions and the turfgrass portion of the oasis treatment was irrigated at a rate of 392.2 l/m^2. Although irrigation rates were similar in pre-monsoon and monsoon conditions, increased atmospheric humidity suppressed the capacity for evaporative cooling in the landscape which resulted in reduced air temperatures in the treatments with turfgrass at elevations up to approximately one meter. Spronken-Smith and Oke (1998) found evaporative cooling in parks to have a greater effect on air temperatures in Sacramento, California than in Vancouver, British Columbia. Relative humidities were not reported, but Spronken-Smith et al. (2000) describe Sacramento's climate as "hot and dry", much like pre-monsoon conditions in Phoenix. It is not unreasonable to assume relative humidity to be a contributing factor in limiting the evaporative cooling potential of turfed areas.

For the most part, there was very little difference in relative humidity (2 m height) across the treatments, regardless of season. The two exceptions are during the monsoon night collection period in the desert treatment, and the winter night collection period in the oasis treatment. The higher humidity in the desert treatment during the monsoon night collection period is due to the large irrigation event that was occurring before and during the data collection period at an adjacent golf course. The lower humidity in the oasis treatment during the winter night collection period is the result of natural variation in synoptic weather conditions.

The evaportranspiration (ETo) during the winter data collection was 14.5 mm. In comparison, the pre-monsoon ETo was 40.4 mm and monsoon ETo was 142.2 mm. Irrigation was determined by daily ETo rates and as a result, irrigation during the winter collection period was minimal. Limited water additions to the landscape in connection with less incoming solar radiation meant there was very little evaportanspirational cooling in the treatments during the winter. Spronken-Smith et al. (2000) suggest turfed park areas act like large, wet leaves in "thermostating" surrounding air temperatures, such that during peak heat input, temperatures of irrigated surfaces may be much lower than the air above it. The temperature profiles show that irrigated treatments had much lower surface temperatures than the synoptic air temperatures and un-irrigated treatments have surface temperatures that are much higher than the synoptic air temperatures.

The results of this study indicate that for residential neighborhoods, the strategic use of turfgrass will provide the benefit of heat mitigation in the region of human activity during the summer months, especially during the hot and dry conditions that dominate Arizona summers. However, unoverseeded landscapes will not impact air temperatures during winter, when heat mitigation is not desirable. Homeowners who wish to maximize the heat mitigation utility of their landscapes but limit water consumption should plant judicious amounts of summer lawns in areas of high human activity. Spronken-Smith and Oke (1998) found that the horizontal influence of parks on air temperature extended into the surrounding area approximately the same width of the park. Results of this study indicate that in the Phoenix climate, surface cover is the dominant influence on near-surface air temperatures. However, since widespread turf, such as found in the mesic treatment, is impractical in the current culture which promotes water conservation, it is desirable to create residential landscape designs that maximize heat mitigation while limiting water consumption. Consequently, more research on the widespread effect of different size turf fragments would provide insights useful for residential landscape designers.

Additionally, this research was conducted on immature landscapes. At the time of data collection, the treatments were only three years old. As a result, shade from the small, young trees did not have a noticeable impact on surface or air temperatures. Research which incorporates the effect of mature shade trees

on microclimates in the Phoenix region will allow for even better landscape design recommendations.

Because this research utilized air temperatures throughout the vertical profile, it will be useful to connect in situ temperatures with data collected through remote sensing. Doing so will enable the creation of better, more accurate models for explaining and predicting the UHI. Current mesoscale models, such as WRF (Weather Research and Forcasting, 2010), are commonly used to predict weather in cities and across regions but are unable to capture fine scale differences within urban settings (The Weather Research & Forecasting Model, 2010). The data presented in this study provide the fine scale resolution in temperature patterns that occur because of differences in landscape design at the neighborhood scale.

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APPENDIX A

MEAN SURFACE AND AIR TEMPERATURES OF ALL DATA POINTS BY SEASON, TIME, TREATMENT AND HEIGHT

Premonsoon Morning

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	39.0	44.5	47.3	50.5	47.6
0.25 m	36.7	37.4	36.5	38.8	36.7
0.5 m	37.0	37.5	36.4	38.6	37.0
1.0 m	36.2	36.5	35.2	37.4	36.2
2.0 m	35.5	35.6	34.5	36.6	35.5
5.0 m	35.7	36.0	34.3	36.1	35.7

Premonsoon Afternoon

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	35.8	47.9	54.0	55.1	52.9
0.25 m	39.7	41.6	43.4	43.1	42.8
0.5 m	40.0	41.8	43.1	42.9	42.6
1.0 m	40.1	41.3	42.2	41.8	41.7
2.0 m	40.1	40.8	40.1	41.2	40.9
5.0 m	40.2	40.5	40.5	40.6	41.7

Premonsoon Night

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	22.3	26.4	29.6	27.8	27.8
0.25 m	27.1	30.0	30.4	29.2	32.3
0.5 m	28.3	30.4	30.6	29.5	32.5
1.0 m	29.2	30.9	30.9	29.8	32.9
2.0 m	30.3	31.4	31.3	30.6	33.2
5.0 m	32.1	32.0	32.3	32.5	33.7

Monsoon Morning

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	34.0	41.6	45.8	45.8	41.0
0.25 m	35.0	38.3	36.6	37.7	34.5
0.5 m	34.8	37.7	35.9	37.3	33.9
1.0 m	34.7	37.2	35.8	36.8	33.5
2.0 m	34.0	35.9	34.2	36.0	32.4
5.0 m	34.5	36.3	34.7	36.9	32.9

Monsoon Night

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	36.1	45.7	49.1	52.9	47.6
0.25 m	38.8	42.9	41.4	42.8	42.2
0.5 m	39.2	42.6	40.9	42.6	53.1
1.0 m	39.3	42.5	40.5	41.7	40.7
2.0 m	39.3	42.0	39.9	41.1	40.4
5.0 m	39.9	41.8	39.9	41.0	40.1

Monsoon Evening

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	22.2	30.9	31.3	33.6	27.4
0.25 m	26.9	32.3	31.7	32.3	31.0
0.5 m	28.5	32.2	31.7	32.2	31.5
1.0 m	29.4	32.2	31.7	32.2	32.0
2.0 m	30.6	31.9	31.6	31.9	32.2
5.0 m	31.3	32.2	31.9	32.3	33.2

Winter Morning

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	12.7	10.8	8.0	6.9	13.1

0.25 m	13.3	12.8	9.6	8.5	13.4
0.5 m	13.3	12.5	9.5	8.3	13.3
1.0 m	13.7	12.4	9.5	8.2	13.7
2.0 m	12.8	11.8	8.9	7.7	12.6
5.0 m	14.8	12.1	9.5	7.6	12.8

Winter Afternoon

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	24.5	24.0	25.1	23.1	28.0
0.25 m	23.4	22.4	20.4	17.6	24.6
0.5 m	23.1	22.4	20.0	17.2	24.3
1.0 m	23.4	22.4	19.8	17.1	24.4
2.0 m	22.4	21.8	18.6	15.7	23.3
5.0 m	23.3	22.2	19.1	16.3	22.9

Winter Night

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	7.3	8.7	8.4	6.9	9.3
0.25 m	11.5	13.4	10.4	9.1	13.6
0.5 m	13.0	14.1	10.6	9.4	14.5
1.0 m	13.6	14.7	10.8	9.7	15.1
2.0 m	14.5	15.5	11.0	9.9	15.5
5.0 m	15.2	16.1	11.9	10.5	16.6

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APPENDIX A

MEAN SURFACE AND AIR TEMPERATURES OF ALL DATA POINTS BY SEASON, TIME, TREATMENT AND HEIGHT

Premonsoon Morning

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	39.0	44.5	47.3	50.5	47.6
0.25 m	36.7	37.4	36.5	38.8	36.7
0.5 m	37.0	37.5	36.4	38.6	37.0
1.0 m	36.2	36.5	35.2	37.4	36.2
2.0 m	35.5	35.6	34.5	36.6	35.5
5.0 m	35.7	36.0	34.3	36.1	35.7

Premonsoon Afternoon

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	35.8	47.9	54.0	55.1	52.9
0.25 m	39.7	41.6	43.4	43.1	42.8
0.5 m	40.0	41.8	43.1	42.9	42.6
1.0 m	40.1	41.3	42.2	41.8	41.7
2.0 m	40.1	40.8	40.1	41.2	40.9
5.0 m	40.2	40.5	40.5	40.6	41.7

Premonsoon Night

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	22.3	26.4	29.6	27.8	27.8
0.25 m	27.1	30.0	30.4	29.2	32.3
0.5 m	28.3	30.4	30.6	29.5	32.5
1.0 m	29.2	30.9	30.9	29.8	32.9
2.0 m	30.3	31.4	31.3	30.6	33.2
5.0 m	32.1	32.0	32.3	32.5	33.7

Monsoon Morning

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	34.0	41.6	45.8	45.8	41.0
0.25 m	35.0	38.3	36.6	37.7	34.5
0.5 m	34.8	37.7	35.9	37.3	33.9
1.0 m	34.7	37.2	35.8	36.8	33.5
2.0 m	34.0	35.9	34.2	36.0	32.4
5.0 m	34.5	36.3	34.7	36.9	32.9

Monsoon Night

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	36.1	45.7	49.1	52.9	47.6
0.25 m	38.8	42.9	41.4	42.8	42.2
0.5 m	39.2	42.6	40.9	42.6	53.1
1.0 m	39.3	42.5	40.5	41.7	40.7
2.0 m	39.3	42.0	39.9	41.1	40.4
5.0 m	39.9	41.8	39.9	41.0	40.1

Monsoon Evening

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	22.2	30.9	31.3	33.6	27.4
0.25 m	26.9	32.3	31.7	32.3	31.0
0.5 m	28.5	32.2	31.7	32.2	31.5
1.0 m	29.4	32.2	31.7	32.2	32.0
2.0 m	30.6	31.9	31.6	31.9	32.2
5.0 m	31.3	32.2	31.9	32.3	33.2

Winter Morning

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	12.7	10.8	8.0	6.9	13.1

0.25 m	13.3	12.8	9.6	8.5	13.4
0.5 m	13.3	12.5	9.5	8.3	13.3
1.0 m	13.7	12.4	9.5	8.2	13.7
2.0 m	12.8	11.8	8.9	7.7	12.6
5.0 m	14.8	12.1	9.5	7.6	12.8

Winter Afternoon

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	24.5	24.0	25.1	23.1	28.0
0.25 m	23.4	22.4	20.4	17.6	24.6
0.5 m	23.1	22.4	20.0	17.2	24.3
1.0 m	23.4	22.4	19.8	17.1	24.4
2.0 m	22.4	21.8	18.6	15.7	23.3
5.0 m	23.3	22.2	19.1	16.3	22.9

Winter Night

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	7.3	8.7	8.4	6.9	9.3
0.25 m	11.5	13.4	10.4	9.1	13.6
0.5 m	13.0	14.1	10.6	9.4	14.5
1.0 m	13.6	14.7	10.8	9.7	15.1
2.0 m	14.5	15.5	11.0	9.9	15.5
5.0 m	15.2	16.1	11.9	10.5	16.6

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MEAN SURFACE AND AIR TEMPERATURES OF ALL DATA POINTS BY SEASON, TIME, TREATMENT AND HEIGHT

Premonsoon Morning

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	39.0	44.5	47.3	50.5	47.6
0.25 m	36.7	37.4	36.5	38.8	36.7
0.5 m	37.0	37.5	36.4	38.6	37.0
1.0 m	36.2	36.5	35.2	37.4	36.2
2.0 m	35.5	35.6	34.5	36.6	35.5
5.0 m	35.7	36.0	34.3	36.1	35.7

Premonsoon Afternoon

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	35.8	47.9	54.0	55.1	52.9
0.25 m	39.7	41.6	43.4	43.1	42.8
0.5 m	40.0	41.8	43.1	42.9	42.6
1.0 m	40.1	41.3	42.2	41.8	41.7
2.0 m	40.1	40.8	40.1	41.2	40.9
5.0 m	40.2	40.5	40.5	40.6	41.7

Premonsoon Night

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	22.3	26.4	29.6	27.8	27.8
0.25 m	27.1	30.0	30.4	29.2	32.3
0.5 m	28.3	30.4	30.6	29.5	32.5
1.0 m	29.2	30.9	30.9	29.8	32.9
2.0 m	30.3	31.4	31.3	30.6	33.2
5.0 m	32.1	32.0	32.3	32.5	33.7

Monsoon Morning

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	34.0	41.6	45.8	45.8	41.0
0.25 m	35.0	38.3	36.6	37.7	34.5
0.5 m	34.8	37.7	35.9	37.3	33.9
1.0 m	34.7	37.2	35.8	36.8	33.5
2.0 m	34.0	35.9	34.2	36.0	32.4
5.0 m	34.5	36.3	34.7	36.9	32.9

Monsoon Night

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	36.1	45.7	49.1	52.9	47.6
0.25 m	38.8	42.9	41.4	42.8	42.2
0.5 m	39.2	42.6	40.9	42.6	53.1
1.0 m	39.3	42.5	40.5	41.7	40.7
2.0 m	39.3	42.0	39.9	41.1	40.4
5.0 m	39.9	41.8	39.9	41.0	40.1

Monsoon Evening

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	22.2	30.9	31.3	33.6	27.4
0.25 m	26.9	32.3	31.7	32.3	31.0
0.5 m	28.5	32.2	31.7	32.2	31.5
1.0 m	29.4	32.2	31.7	32.2	32.0
2.0 m	30.6	31.9	31.6	31.9	32.2
5.0 m	31.3	32.2	31.9	32.3	33.2

Winter Morning

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	12.7	10.8	8.0	6.9	13.1

0.25 m	13.3	12.8	9.6	8.5	13.4
0.5 m	13.3	12.5	9.5	8.3	13.3
1.0 m	13.7	12.4	9.5	8.2	13.7
2.0 m	12.8	11.8	8.9	7.7	12.6
5.0 m	14.8	12.1	9.5	7.6	12.8

Winter Afternoon

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	24.5	24.0	25.1	23.1	28.0
0.25 m	23.4	22.4	20.4	17.6	24.6
0.5 m	23.1	22.4	20.0	17.2	24.3
1.0 m	23.4	22.4	19.8	17.1	24.4
2.0 m	22.4	21.8	18.6	15.7	23.3
5.0 m	23.3	22.2	19.1	16.3	22.9

Winter Night

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	7.3	8.7	8.4	6.9	9.3
0.25 m	11.5	13.4	10.4	9.1	13.6
0.5 m	13.0	14.1	10.6	9.4	14.5
1.0 m	13.6	14.7	10.8	9.7	15.1
2.0 m	14.5	15.5	11.0	9.9	15.5
5.0 m	15.2	16.1	11.9	10.5	16.6

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APPENDIX A

MEAN SURFACE AND AIR TEMPERATURES OF ALL DATA POINTS BY SEASON, TIME, TREATMENT AND HEIGHT

Premonsoon Morning

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	39.0	44.5	47.3	50.5	47.6
0.25 m	36.7	37.4	36.5	38.8	36.7
0.5 m	37.0	37.5	36.4	38.6	37.0
1.0 m	36.2	36.5	35.2	37.4	36.2
2.0 m	35.5	35.6	34.5	36.6	35.5
5.0 m	35.7	36.0	34.3	36.1	35.7

Premonsoon Afternoon

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	35.8	47.9	54.0	55.1	52.9
0.25 m	39.7	41.6	43.4	43.1	42.8
0.5 m	40.0	41.8	43.1	42.9	42.6
1.0 m	40.1	41.3	42.2	41.8	41.7
2.0 m	40.1	40.8	40.1	41.2	40.9
5.0 m	40.2	40.5	40.5	40.6	41.7

Premonsoon Night

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	22.3	26.4	29.6	27.8	27.8
0.25 m	27.1	30.0	30.4	29.2	32.3
0.5 m	28.3	30.4	30.6	29.5	32.5
1.0 m	29.2	30.9	30.9	29.8	32.9
2.0 m	30.3	31.4	31.3	30.6	33.2
5.0 m	32.1	32.0	32.3	32.5	33.7

Monsoon Morning

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	34.0	41.6	45.8	45.8	41.0
0.25 m	35.0	38.3	36.6	37.7	34.5
0.5 m	34.8	37.7	35.9	37.3	33.9
1.0 m	34.7	37.2	35.8	36.8	33.5
2.0 m	34.0	35.9	34.2	36.0	32.4
5.0 m	34.5	36.3	34.7	36.9	32.9

Monsoon Night

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	36.1	45.7	49.1	52.9	47.6
0.25 m	38.8	42.9	41.4	42.8	42.2
0.5 m	39.2	42.6	40.9	42.6	53.1
1.0 m	39.3	42.5	40.5	41.7	40.7
2.0 m	39.3	42.0	39.9	41.1	40.4
5.0 m	39.9	41.8	39.9	41.0	40.1

Monsoon Evening

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	22.2	30.9	31.3	33.6	27.4
0.25 m	26.9	32.3	31.7	32.3	31.0
0.5 m	28.5	32.2	31.7	32.2	31.5
1.0 m	29.4	32.2	31.7	32.2	32.0
2.0 m	30.6	31.9	31.6	31.9	32.2
5.0 m	31.3	32.2	31.9	32.3	33.2

Winter Morning

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	12.7	10.8	8.0	6.9	13.1

0.25 m	13.3	12.8	9.6	8.5	13.4
0.5 m	13.3	12.5	9.5	8.3	13.3
1.0 m	13.7	12.4	9.5	8.2	13.7
2.0 m	12.8	11.8	8.9	7.7	12.6
5.0 m	14.8	12.1	9.5	7.6	12.8

Winter Afternoon

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	24.5	24.0	25.1	23.1	28.0
0.25 m	23.4	22.4	20.4	17.6	24.6
0.5 m	23.1	22.4	20.0	17.2	24.3
1.0 m	23.4	22.4	19.8	17.1	24.4
2.0 m	22.4	21.8	18.6	15.7	23.3
5.0 m	23.3	22.2	19.1	16.3	22.9

Winter Night

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	7.3	8.7	8.4	6.9	9.3
0.25 m	11.5	13.4	10.4	9.1	13.6
0.5 m	13.0	14.1	10.6	9.4	14.5
1.0 m	13.6	14.7	10.8	9.7	15.1
2.0 m	14.5	15.5	11.0	9.9	15.5
5.0 m	15.2	16.1	11.9	10.5	16.6

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MEAN SURFACE AND AIR TEMPERATURES OF ALL DATA POINTS BY SEASON, TIME, TREATMENT AND HEIGHT

Premonsoon Morning

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	39.0	44.5	47.3	50.5	47.6
0.25 m	36.7	37.4	36.5	38.8	36.7
0.5 m	37.0	37.5	36.4	38.6	37.0
1.0 m	36.2	36.5	35.2	37.4	36.2
2.0 m	35.5	35.6	34.5	36.6	35.5
5.0 m	35.7	36.0	34.3	36.1	35.7

Premonsoon Afternoon

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	35.8	47.9	54.0	55.1	52.9
0.25 m	39.7	41.6	43.4	43.1	42.8
0.5 m	40.0	41.8	43.1	42.9	42.6
1.0 m	40.1	41.3	42.2	41.8	41.7
2.0 m	40.1	40.8	40.1	41.2	40.9
5.0 m	40.2	40.5	40.5	40.6	41.7

Premonsoon Night

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	22.3	26.4	29.6	27.8	27.8
0.25 m	27.1	30.0	30.4	29.2	32.3
0.5 m	28.3	30.4	30.6	29.5	32.5
1.0 m	29.2	30.9	30.9	29.8	32.9
2.0 m	30.3	31.4	31.3	30.6	33.2
5.0 m	32.1	32.0	32.3	32.5	33.7

Monsoon Morning

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	34.0	41.6	45.8	45.8	41.0
0.25 m	35.0	38.3	36.6	37.7	34.5
0.5 m	34.8	37.7	35.9	37.3	33.9
1.0 m	34.7	37.2	35.8	36.8	33.5
2.0 m	34.0	35.9	34.2	36.0	32.4
5.0 m	34.5	36.3	34.7	36.9	32.9

Monsoon Night

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	36.1	45.7	49.1	52.9	47.6
0.25 m	38.8	42.9	41.4	42.8	42.2
0.5 m	39.2	42.6	40.9	42.6	53.1
1.0 m	39.3	42.5	40.5	41.7	40.7
2.0 m	39.3	42.0	39.9	41.1	40.4
5.0 m	39.9	41.8	39.9	41.0	40.1

Monsoon Evening

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	22.2	30.9	31.3	33.6	27.4
0.25 m	26.9	32.3	31.7	32.3	31.0
0.5 m	28.5	32.2	31.7	32.2	31.5
1.0 m	29.4	32.2	31.7	32.2	32.0
2.0 m	30.6	31.9	31.6	31.9	32.2
5.0 m	31.3	32.2	31.9	32.3	33.2

Winter Morning

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	12.7	10.8	8.0	6.9	13.1

0.25 m	13.3	12.8	9.6	8.5	13.4
0.5 m	13.3	12.5	9.5	8.3	13.3
1.0 m	13.7	12.4	9.5	8.2	13.7
2.0 m	12.8	11.8	8.9	7.7	12.6
5.0 m	14.8	12.1	9.5	7.6	12.8

Winter Afternoon

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	24.5	24.0	25.1	23.1	28.0
0.25 m	23.4	22.4	20.4	17.6	24.6
0.5 m	23.1	22.4	20.0	17.2	24.3
1.0 m	23.4	22.4	19.8	17.1	24.4
2.0 m	22.4	21.8	18.6	15.7	23.3
5.0 m	23.3	22.2	19.1	16.3	22.9

Winter Night

Height	Mesic °C	Oasis °C	Xeric °C	Desert °C	Control °C
Surface	7.3	8.7	8.4	6.9	9.3
0.25 m	11.5	13.4	10.4	9.1	13.6
0.5 m	13.0	14.1	10.6	9.4	14.5
1.0 m	13.6	14.7	10.8	9.7	15.1
2.0 m	14.5	15.5	11.0	9.9	15.5
5.0 m	15.2	16.1	11.9	10.5	16.6