ECOSYSTEM FUNCTION OF URBAN PLANTS

IN RESPONSE TO LANDSCAPE MANAGEMENT

by

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ABSTRACT

The functional ecology of plants in urban ecosystems is poorly understood relative to natural and agro-ecosystems. Sound management strategies are needed to facilitate sustainable development of urbanized regions. This dissertation examines effects of landscape management on the functional ecology of woody plants in an urban ecosystem at several scales. Landscape management is specifically defined as human alteration of land cover and plant distribution, addition of supplemental water to landscape plants via irrigation, and the removal of plant biomass via pruning. Aspects of plant functional ecology addressed in this dissertation include plant effects on microclimate, carbon sequestration and storage, and water cycling.   Socioeconomic land use influenced land and woody plant canopy cover and urban microclimates. The most common land use in the urbanized study area was single family residential (SFR). Woody plant canopy area was the highest in SFR plots, but did not differ significantly from other land uses due to high variance. The greatest disparity in microclimate as a function of land use occurred during pre-dawn summer hours. Agricultural and residential land uses had the highest relative humidities, dew point temperatures, and normalized differential vegetation index (NDVI) with lowest air temperatures (T). Commercial land uses and industrial areas had the highest T and the lowest NDVI. Generally, T negatively correlated to NDVI and atmospheric moisture positively correlated to NDVI. In experimental plots designed to resemble local SFR sites in number and life forms of vegetation present, irrigation rate and pruning regimes influenced plant productivity (PP), average standing canopy leaf area (LA), and irrigation water use efficiency (WUE_I). Whole plot PP and LA were higher and WUE_I was lower under high irrigation rate as compared to low irrigation rate.

Whole plot carbon acquisition and transpiration potentials were influenced by treatment effects on LA. Data indicate that landscape management practices might most influence the plant ecosystem functions examined in this study via changes in vegetation density and LA and that plant distribution, irrigation, and pruning might be modified to optimize plant effects on microclimate and landscape carbon and water dynamics.

ACKNOWLEDGEMENTS

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CHAPTER 1: INTRODUCTION

Problem Statement

The concept of cities as planned and managed ecosystems is a relatively new one. Botkin and Beveridge (1997) stress the importance of this concept in noting that cities are an integral part of human civilization and that the world is becoming more and not less urbanized. They suggest that to practice biological conservation and address other environmental issues while creating pleasant environments for human beings, cities need to be understood and managed as functioning urban ecosystems.

The ecology of plants in cities is poorly understood relative to natural and agro-ecosystems, and heterogeneity of plant populations and management of urban plants should be considered when making predictions about urban ecosystem processes. Plants function in urban ecosystems to sequester and store carbon, to cycle water and improve air quality, and as climate modifiers and wildlife habitat, in addition to creating more pleasant urban environments for humans (Huang, et al., 1992; Rowntree et al., 1994; Bolund and Hunhammar, 1999). Currently, management of urban plants emphasizes human comfort, safety, and aesthetics (Miller, 1997) possibly because neither the role of plants in the urban ecosystem nor the effects of management on plant ecology is well understood. As urbanization has increased and environmental concerns gain public interest, research emphases have begun to shift towards management of urban plants to maximize more environmentally centered ecosystem services as well (McPherson, 1994; Nowak, 2002)

Environmental horticulturists and agronomists have long recognized the extent to which human management can influence plant ecophysiology and their research has focused on the effects of irrigation, fertilization, and manipulation of the physical and edaphic environment on plant productivity and performance. The focus of ornamental horticulturists has traditionally been to evaluate plant materials and to improve nursery production and post-production performance of plants in urban landscape settings. Many researchers have examined limitations to plant performance in urban environments (Whitlow and Bassuk, 1988; Kjelgren and Clark, 1992, Montague, et al. 2000; Grabowsky et al., 2001). In arid and semi-arid climates, recent interest in issues such as water conservation has led to some ecophysiological studies of urban amenity landscape plants and water use (Devitt et al., 1995; Kjelgren, 2000; Martin and Stabler, 2002).

Urban foresters have traditionally held a somewhat different perspective of urban plant management and ecology. Their focus has typically been restricted to long term planning and maintenance for tree dominated, urban and peri-urban areas such as woodlands, parks, nature areas, and street trees (Nowak, 1996; Miller, 1997). Recent trends in urban forestry research include an emphasis on describing the broad spatial scale ecology of urban forests (McPherson, 1997; Nowak, 2002) without consideration of how heterogeneous human management practices affect urban forest ecosystem function. In recent years forest ecologists have expanded the definition of urban forests to include all woody and herbaceous plants and associated soil in urban environments (Rowntree, et al. 1984), perhaps a more appropriate definition to the study of urban ecosystems. In contrast to most forest systems, urban forests in this most inclusive sense are characterized by heterogeneity and complexity and presented unique research challenges.

Trends in urban planning and landscape architecture also increasingly seek to incorporate knowledge of ecosystem processes into urban environments.

The new paradigm of the city as a managed ecosystem creates a need to integrate the sciences of landscape and environmental horticulture, urban forestry, and plant ecophysiology to fully understand the role and function of urban plants. The extreme environment of the Sonoran Desert, in which the Phoenix, Arizona, metropolitan area is situated, and the intensive manipulation of that environment to support amenity landscapes provide a unique perspective from which to study urban plant ecological function and how it is affected by human management practices. The intent of this dissertation is to integrate concepts from landscape horticulture, plant ecophysiology, urban forestry and urban climatology to examine how specific human management practices affect some of the ecosystem functions of plants in urban settings.

Landscape Management

Landscape management influences the functional ecology of plants at multiple scales, and each of these scales has traditionally fallen under the realm of different plant management perspectives. In Phoenix, Arizona, the conversion of desert or agricultural lands to urban land uses represents relatively broad spatial and temporal scale changes in landscape plant distribution, productivity, and water cycling (Martin and Stabler, 2002). Current trends in long term and regional scale land use planning include incorporation of urban forestry programs to plan for and manage urban vegetation and open space via integration of multidisciplinary expertise and perspectives (Miller, 1997; Bradley, 1995).

Within urban ecosystems, landscape management creates a heterogeneous mosaic of landscape patches, often with distinct boundary edges defined by land use and ownership (Pickett and Cadenasso, 1995). A landscape patch can be defined as "a relatively homogeneous area that differs from its surroundings" (Foreman, 1985). Land cover and plant distribution in cities range in a continuum of complete cover by man-made structures and surfaces to areas such as parks and preserves that retain many properties of the undisturbed landscape (McDonnell and Pickett, 1990), and plant function is defined by the socioeconomic or environmental function of the land use. Spatial heterogeneity of vegetation and cover by other surfaces such as concrete and asphalt in urban landscapes influence ecosystem attributes such as microclimate, nutrient and water cycling, and possibly local CO_2 concentrations (Oke 1988; Grimmond and Oke; 1991, Idso, et al., 1998; Green and Oleksyszyn, 2002). A combination of decisions and activities by municipal ordinances, landscape architects and contractors, and the horticulture industry influence the structure and composition of the urban vegetation community (Miller, 1997).

Further heterogeneity in plant function exists at the scale of individually owned and managed landscape patches, due to variation in plant distribution, species composition and maintenance practices (Martin and Stabler, 2002). The degree to which individual management practices influence the overall function of the urban forest is unknown. Management of urban landscapes, including production, installation and maintenance of plants, is the traditional realm of landscape horticulture, and the primary perspective from which this work is conducted.

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This dissertation examines effects of landscape management on the function of woody plants in an urban ecosystem at several scales. Landscape management is specifically defined as deliberate human alteration of land cover and plant distribution, addition of supplemental water to landscape plants via irrigation, and the removal of plant biomass via pruning. First, via collaborative effort with the Central Arizona Phoenix Long Term Ecological Research (CAP-LTER) survey 200 project, an examination of the effects of socioeconomic land use on land cover and plant distribution in the Phoenix metropolitan area serves as a broad spatial scale descriptor of the study area. Next, a study of the effects of temporal and spatial changes in intra-urban land use on normalized differential vegetation index (NDVI) and urban microclimates is presented. Finally, the effects of plant maintenance practices, specifically irrigation and pruning, on woody plant growth, average canopy leaf area, and physiological function are scaled from leaf to the whole plot (landscape patch) level and the implications to landscape management are discussed.

Ecosystem function of urban plants

Three interrelated aspects of urban plant ecosystem function are addressed by this work. First, the relationships between land use, NDVI and urban microclimates are examined over space and time in several areas of the CAP-LTER study area. Second, woody plant carbon uptake and storage is examined as a function of irrigation and pruning regimes, and is scaled to the whole plot level to offer predictions about plant canopy cover and resultant ecosystem function at that spatial scale. Third, plant water cycling as a function of irrigation, pruning and plant distribution and its potential effects

on plant growth and landscape level productivity, evapotranspiration, and microclimate are discussed. Finally, the concept of plant water use efficiency (WUE) is discussed in terms of managed amenity landscape plants. All data are considered in light of the survey 200 description of the CAP-LTER study to provide a general overview of landscape management and plant functional ecology in an urbanized desert ecosystem.

Potential contributions and limitations

Research initiatives such as the CAP-LTER (http://caplter.asu.edu/), the Arizona State University IGERT in Urban Ecology (http://www.asu.edu/ces/igert.htm), the Greater Phoenix 2100 (http://www.gp2100.org/), and the Consortium for the Study of Rapidly Urbanizing Regions (http://ces.asu.edu/csrur/) recognize the need to incorporate multidisciplinary approaches in understanding urban ecosystems to best manage them for long term sustainability. From a basic research perspective, data presented in this dissertation provide a strong foundation for future long-term investigations of plant ecology in the CAP-LTER ecosystem. In addition, the applied horticultural research conducted is readily disseminated and can be quickly incorporated into local landscape management decisions.

The greatest limitation of this work is the ability to accurately scale up from the landscape plot or patch level to land use or urban ecosystem level with the available data, and when such exercises are undertaken in the final chapter, it is to make generalizations rather than to suggest matters of fact. Other specific limitations to the data and analyses are discussed within the appropriate chapters.

CHAPTER 2: LAND AND VEGETATION COVER IN AN URBAN DESERT ECOSYSTEM

Summary

An extensive field survey of 107 randomly chosen, 30m x 30m site sites was conducted during spring 2000 to describe the biotic and abiotic land cover characteristics of the developed portions of the Central Arizona Phoenix Long Term Ecological Research (CAP- LTER) study area. Sites were located using a global positioning system, predominant dominant land use was determined, and land and plant canopy cover characteristics were mapped and measured. The majority (53.3%) of randomly chosen plots in the metropolitan area were single family residential (SFR) and 10.3% were characterized by transportation (roads and airports). Commercial and vacant (or under construction) sites accounted for 8.4% of land use each, and 7.5% of sites were classified as institutional (churches, schools, libraries, etc.). Other land uses included multifamily residential (4.7%), recreation areas (parks and golf courses, 2.8%), waterways (canals and irrigation ditches, 2.8%), and industrial areas (1.9%). Plots differed in terms of land surface and plant canopy coverage as a function of land use.   Commercial plots had the highest percentage of impervious land cover; vacant sites, recreational areas and waterways had the lowest. Commercial and transportation sites had high cover by asphalt, while vacant sites and waterways were dominated by soil. Cover in recreation areas was mostly vegetation (turf and herbaceous ground covers), while all other land uses had a mix of land covers, including those mentioned above as well as concrete, gravel, metal, tile and tarpaper roofs, and water. Average building height was similar

across land use on sites with anthropogenic structures. Plant canopy area was highest in

SFR plots, averaging 131.8 m^2, but did not differ significant from other land uses due to

high variance and unequal sample sizes. These data offer a detailed description of some

physical surface characteristics and plant canopy cover in the urbanized Phoenix

metropolitan area.

Introduction

Urban planning and zoning laws regulate the pattern and morphology of urban

landscapes (Platt, 1991).   Though vegetation has always played a significant role in the

human environment, in recent years a growing interest in urban ecosystems has expanded

the role of the urban forester to be involved in the planning process to include and

maintain vegetation for amenity and recreation, practical function, environmental

services, and sustainable development in urban landscapes (Bradley, 1995).

The most traditional concept of the structure of an urban forest divides the landscape

into distinctive zones from the city center outward, forming an urban to rural gradient of

low to high vegetation density (Miller, 1997). This model is based on cities of the eastern

United States and fails to consider the heterogeneous landscape mosaic described by

Pickett and Cadenasso (1995). Other studies of urban ecosystems suggest that

socioeconomic land use might be a better predictor of land and vegetation cover than

proximity to the city center (Auer, 1978; Nowak, et al. 1994; Pauleit and Duhme, 2000),

particularly in sprawling metropolitan areas such as Phoenix with multiple urban centers

and surrounding suburbs.

Land and vegetation cover characteristics are important determinants of urban energy balance and hydrology, as well as influencing aesthetics and human comfort and well being. In cities, alterations in hydrology due to loss of pervious surface area can increase runoff and reduce water storage capacity, thereby reducing evaporative cooling of the air. While surfaces such as buildings, streets and walks absorb and reradiate thermal energy, plants influence microclimate primarily by altering energy and water balances through shading and evapotranspiration (Grimmond, et al., 1996; Simpson and McPherson, 1998; Sailor, 1998). Existing models suggest that urban vegetation cover might have the greatest impact on microclimate in hot, arid regions such as Phoenix due to effects of irrigation enhanced evapotranspiration during dry summer seasons (Grimmond and Oke, 1999). Urban landscapes and microclimates affect plant physiological function as well and plant stressors such as restricted root zones, high temperature extremes, and limited water availability are common in urban settings (Whitlow and Bassuk, 1988; Kjelgren and Clark, 1992; Montague, et al. 2000; Grabowsky et al., 2001; Celestian and Martin, 2002). Preliminary research conducted in the Phoenix area showed that high temperature limited plant CO_2 assimilation and reduced water use efficiency in irrigated landscapes during summer months (Martin and Stabler, 2002), a phenomenon likely exacerbated by harsh urban microclimates (Celestian and Martin, 2002).

The data presented here describe the land surface and vegetation canopy cover in the Central Arizona Phoenix Long Term Ecological Research (CAP-LTER) study area as a function of management via zoning and socioeconomic land use. The ensuing discussion addresses the implications for plant ecosystem function.

Methods

Study Area

Phoenix, Arizona, (33°26'N, 112°1'W) is situated within the lower Salt River basin on the northeastern edge of the Sonoran Desert in the southwestern United States. Mean annual precipitation in the Phoenix area is 180 mm with approximately 50% occurring as late summer thunderstorms, the remainder normally associated with winter frontal systems originating in the Pacific Ocean (Sellers and Hill, 1974). Summer temperatures average 30.8°C and winters are mild with average temperatures of 11.3°C.

Archeological evidence indicates that the Native American peoples made extensive use of land there for agricultural purposes over 500 years ago by constructing canals (Gammage, 1999). During the late 19th century, European American settlers refurbished those canals, enabling Phoenix to grow rapidly as an agricultural community.   During the last half of the 20th century, much of these formerly agricultural lands have been displaced by suburban residential and commercial development. Currently, the Phoenix metropolitan area is one of the most rapidly expanding in the US; the Morrison Institute for Public Policy (1998) reported that urban development during the 1990's was proceeding at over "an acre an hour". New construction encroaches on desert lands previously undisturbed by agricultural activities, and land use changes within the city boundaries are common. This condition of rapid change can be expected to influence plant distribution, species composition, edaphic conditions, and landscape management regimes.

Data collection and analysis

Study sites were randomly sampled within the CAP-LTER study area using a dual density, tessellation-stratified sampling design (Stevens, 1997). A grid of 4-km x 4-km cells was superimposed on the entire study area, and one sample site was randomly located within each grid cell for the urbanized area, and one site for every 3 cells was sampled from the undeveloped areas outside the urbanized core. Of the final 204 sites sampled, 107 were classified as urban/built up, and the remaining sites were either desert (73) or agricultural (23) lands. The data presented here represent only the urbanized portion of the study area.

Each survey site was located via a global positioning system (GPS) and consisted of a 30m x 30m square plot centered on a randomized coordinate point and ground surveys of the plots were conducted during spring 2000. Dominant land use of each plot was determined based on socioeconomic use and function of structures present, degree of site development, and observed human activity (American Planners Association, 2002). Plot land surface cover characteristics were recorded both on hand drawn maps and using the GPS unit (Trimble Pro XL mapping grade unit). Turf grass and other vegetative ground covers were included in the land cover analysis and not the plant canopy area analysis. Plant canopy area of trees and shrubs over the land surface cover was hand measured as diameter in north-south and east-west directions using meter tapes. Where built structures were present, height of each building was measured using either meter tapes or a clinometer.

Each GPS derived plot map was downloaded into Arcview® geographic information systems (GIS) software and minor corrections were made by overlaying GPS maps on

high resolution aerial photographs of the Phoenix metropolitan area, georeferenced to

UTM.   Hand drawn maps were also used as a reference and to characterize land and roof

surface cover material. Arcinfo® software was used to create polygons from the overlaid

GPS arcs and to calculate area for each cover type. Plant canopy shape was defined as

rectangular or circular and area was calculated as either:

$$A = NS * EW \text{ or} \qquad\qquad\qquad \textit{Eq. 1}$$

$$A = \pi \, (0.5 * ((NS + EW)/2))^2 \qquad\qquad \textit{Eq. 2}$$

where A is canopy area, NS is the measured north/south dimension of canopy, and EW is

the measured east/west dimension of canopy. A rounded plant canopy is therefore

considered a circle with a radius of half the average canopy diameter.

For each 900 m^2 plot, the percent coverage by asphalt, concrete, metal, tarpaper and

tile roofing material (impervious surfaces) and gravel, soil, water, and vegetative ground

cover (pervious surfaces) was calculated. Other covers included brick and wood, but

because the average cover by these surfaces was less than 0.01% for all land uses those

data were deleted. Data were then arcsin transformed and mean percent land cover and

woody plant canopy area was calculated for each land use type. An analysis of variance

(ANOVA) using type IV sums of squares with land use as the independent variable was

conducted using the SAS general linear model and treatment means compared using

Duncan's Multiple Range Test with α set at 0.05.

Results

Within the Phoenix urbanized area, 53.3% of randomly chosen plots were single family residential, 10.3% were classified as transportation (roads and airports), 8.4% were commercial, 8.4% were vacant or under construction, and 7.5% were classified as institutional and included schools, libraries, and churches (figure 2.1). Other land uses comprised less than 5% of the total each and included multifamily residential (5 sites), recreation areas (parks and golf courses, 3 sites), waterways (canals and irrigation ditches, 3 sites), and industrial areas (2 sites, figure 2.1).

Land use had a significant affect on percent cover by impervious surfaces. Impervious surfaces included asphalt, concrete, and roofs made of metal, tarpaper or tile. Commercial plots had the highest percentage of impervious land cover with 78.1%, while sites under construction, recreational areas, and waterways and had the lowest with 17.0%, 8.4% and 6.8 %, respectively (figure 2.2). Other land uses had intermediate cover by impervious surfaces. Land use had a significant affect on mean plant canopy cover and cover by all surfaces materials except concrete, metal, or tile (Table 2.1). Commercial and transportation sites had the most surface covered by asphalt, with 46.2% and 42.4%, respectively. Recreational land uses had the highest percentage of ground covered by vegetation with 45.5% (data not shown), but did not differ significantly from institutional (28.1%), single family residential (22.5%), or multifamily residential land uses (21.1%, figure 2.3).
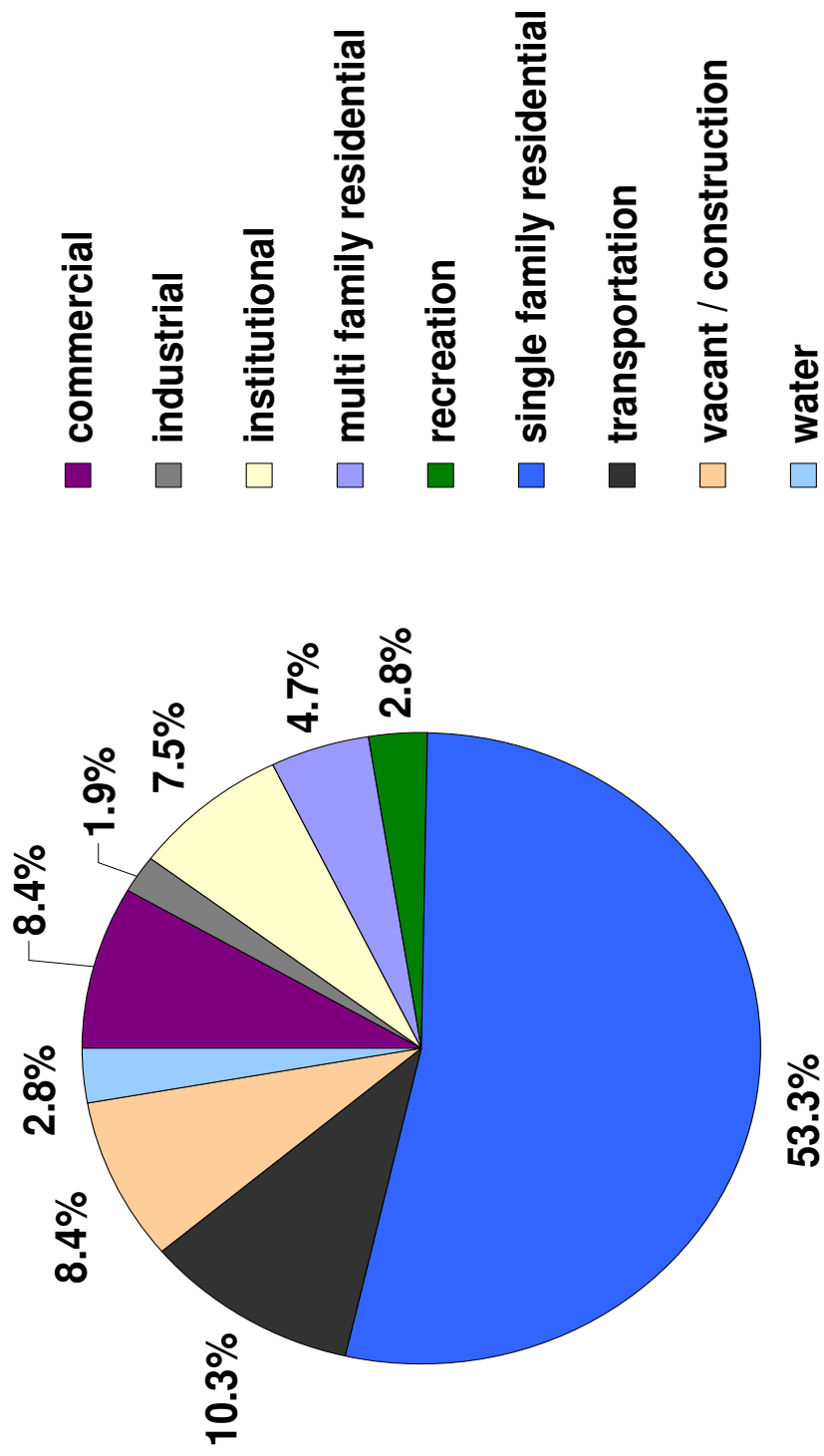
Figure 2.1. Land use classification for 107-30 x 30 m, randomly chosen sites with the Phoenix, Arizona metropolitan area based on zoned socioeconomic use and function of structures present, degree of site development, and observed human activity.
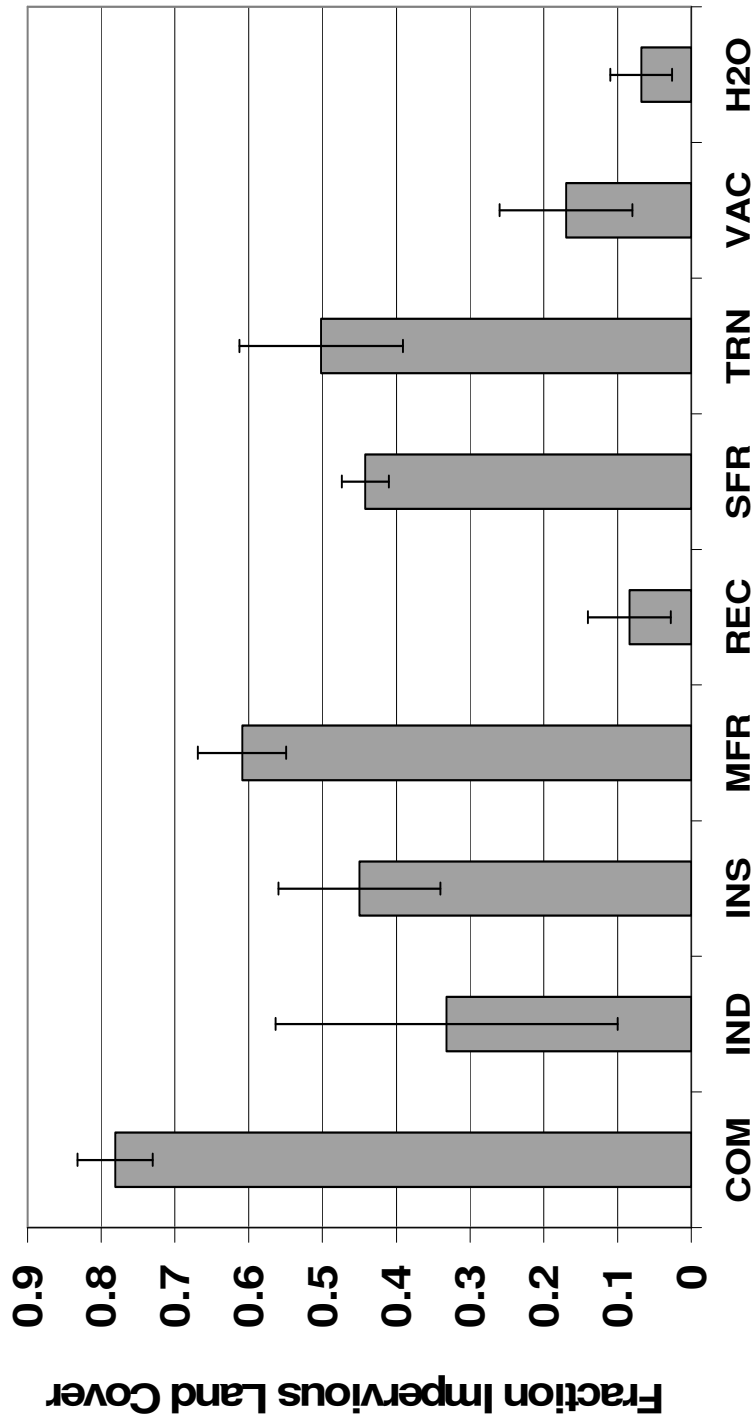
Figure 2.2. Fraction of land surface cover by impervious material (asphalt, concrete, roof materials, etc.) as a function of land use in commercial (COM n= 9) industrial (IND n= 2) institutional (INS n=8) multi family residential (MFR n= 5) recreational (REC n=3) single family residential (SFR n= 54) transportation (TRN n=11) vacant or construction (VAC n=9) or waterway (H2O n=3) in 107 randomly chosen 30 x 30 m sites with the Phoenix, Arizona metropolitan area. Errors bars are +/- 2 SE.

Table 2.1. Analysis of variance probabilities for main effect of land use on land or roof surface cover and plant canopy area.

Surface cover	Pr>F
Asphalt	<0.01
Concrete	0.35
Gravel	0.04
Metal	0.25
Soil	<0.01
Tar paper	<0.01
Tile	0.48
Vegetation	<0.01
Water	<0.01
Plant canopy	<0.01
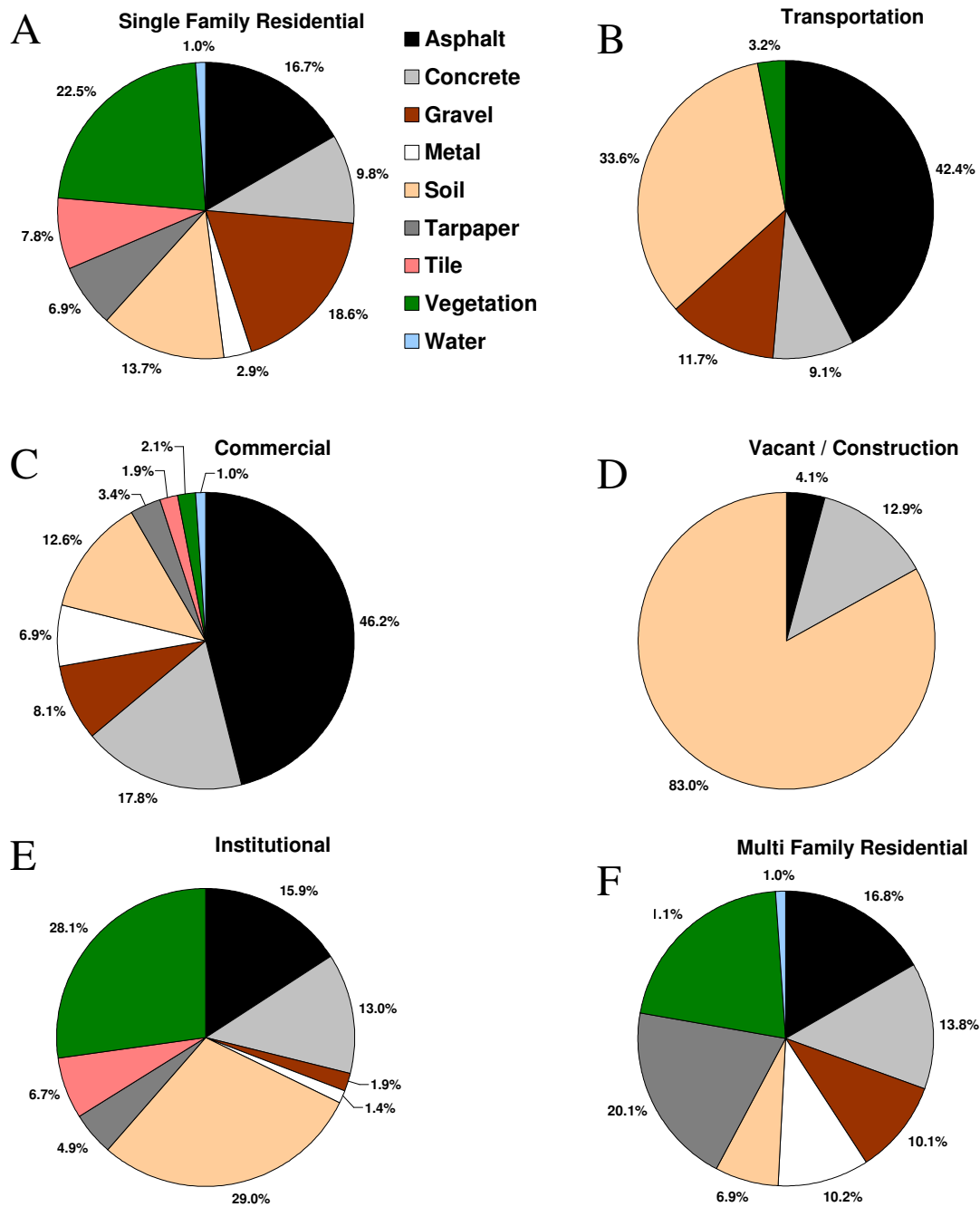
Figure 2.3. Land or roof surface characteristics for predominant land uses in the Phoeinx, Arizona metropolitan area, including (A) single family residential (B) transportation (C) commercial (D) vacant or construction (E) institutional or (F) multifamily residential land uses. Cover characteristics for land uses comprising less than 3% of the study sites (recreational, waterways, and industrial land uses) are not shown.
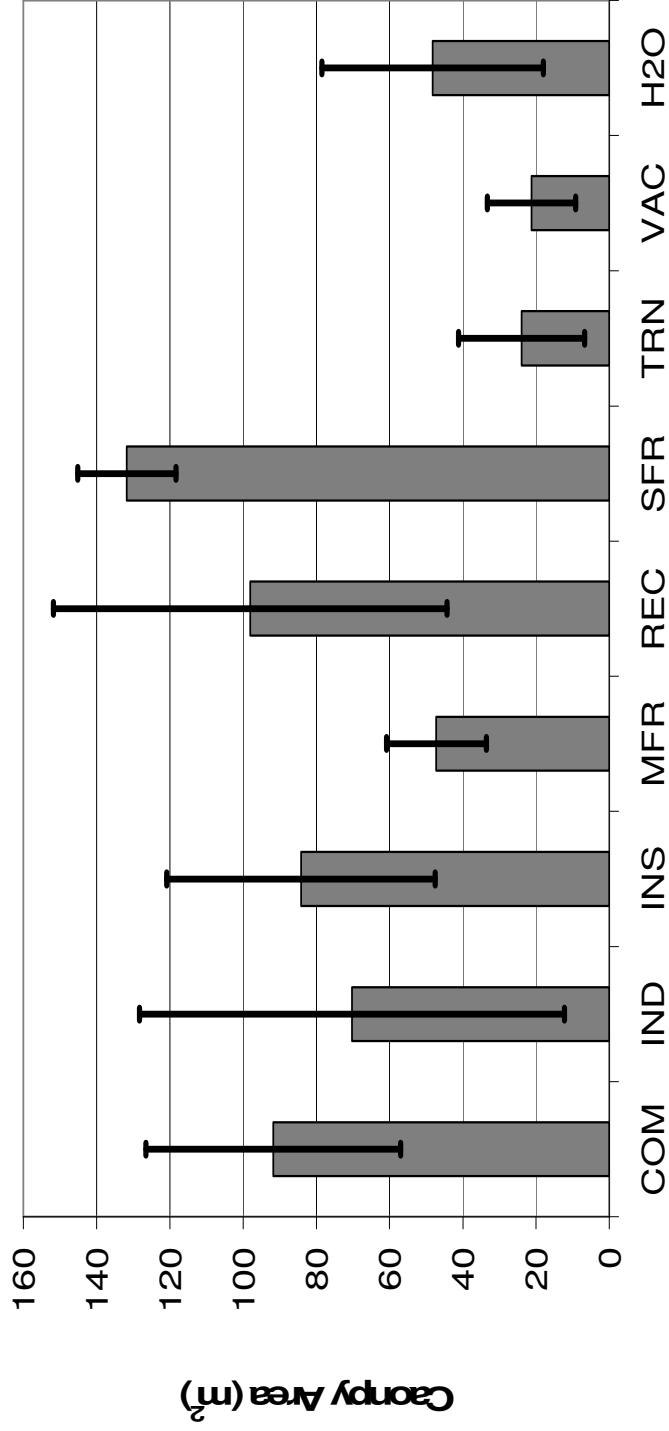
Figure 2.4. Mean 2-dimension, above ground plant canopy area per 30 x 30 m plot as a function of land use in commercial (COM n= 9) industrial (IND n= 2) institutional (INS n=8) multi family residential (MFR n= 5) recreational (REC n=3) single family residential (SFR n= 54) transportation (TRN n=11) vacant or construction (VAC n=9) or waterway (H2O n=3) in 107 randomly chosen 30 x 30 m sites with the Phoenix, Arizona metropolitan area. Errors bars are +/- 2 SE.

Commercial and transportation land uses had decreased ground cover by vegetation relative to other developed land uses with 1.6% and 3.4%, respectively, and sites under construction had no surface vegetation cover. Mean plant canopy area was highest in single family residential plots, averaging 131.8 m^2, but did not differ significantly from most other developed land uses, likely due to high variance and small sample sizes for other land uses (figure 2.4). Average building height was similar across land use on sites with anthropogenic structures (data not shown).

Discussion

These data offer a detailed description of randomly chosen plots across a Sonoran Desert urban ecosystem. They give a quantitative characterization of the physical environment of the CAP-LTER study area at a broad ecosystem scale. Characterization of land cover for some land uses, such as industrial, was limited due to the small number of sites sampled. Conversely, characterization of the predominant land use, SFR, was likely more useful (n=57), and SFR land use will be the focus of this dissertation.

It is well documented that changes in land and plant canopy cover associated with urbanization affect air and surface temperatures, atmospheric and soil moisture, and hydrology of cities (Sanders, 1986; Henry and Dicks, 1987; Pauleit and Duhme, 2000). Each of these factors can in turn affect ecological processes such as photosynthesis and respiration (carbon balance), biotic uptake and release of important nutrient elements such as nitrogen and phosphorus, and physical processes such as erosion and infiltration. Changes associated with urbanization also drastically alter habitat in terms of suitability to support and/or attract biotic populations such as microbes (bacteria and fungi), plants,

and animals (Frankie and Ehler, 1978; Rebele, 1994; Duhme and Pauleit, 1998; Stutz and Martin 1998; Stabler, et al. 2001).

Knowledge of pervious and impervious surface area can be used to make estimates of run-off in water balance equations (Grimmond, 1991; Pauleit and Duhme, 2000). An analysis of the relationship between land cover and precipitation runoff conducted in Munich showed that infiltration of precipitation was estimated to be about 30% for areas with <10% impervious ground cover, about 19% for areas with 30-40% impervious cover, and only about 3% for areas with 60-70% impervious cover (Pauleit and Duhme, 2000). In the Phoenix area, where annual precipitation averages 180 mm per year and mean impervious surface area is about 36% (figure 2.3), a 19% infiltration rate would equate to only about 34 mm infiltrated precipitation for the urban landscape on average.

Using the descriptive data presented here, some values for energy balance equations can be calculated based on knowledge of factors such as albedo, heat absorption and heat storage capacity of surfaces at any given site type. A common value for albedo attributed to urban areas is 0.15 (Campbell and Norman, 1998; Sailor, 1998). Using data from this study, a more accurate value based on knowledge of the relative percentage of each surface type for each land use and the albedo of each surface material might elicit considerable variation in albedo for urban landscapes. For instance, using literature values for land surface cover albedos and weighting each as a fraction of cover in various land uses, a typical commercial patch in Phoenix might have an albedo of 0.17, while a vacant site's albedo might be 0.33 (Table 2.2). Assuming equal total incoming solar radiation of $5.0 \times 10^{7}\,\mathrm{J\,m^{-2}}$ on a clear day for two 30m x 30m sites (200 point survey sampling size) of these disparate intra urban land uses, the difference in absorbed energy

for commercial and vacant sites would be 7.2 x 10^9 J per day. If we incorporate the

commonly assumed urban albedo value of 0.15, calculated values for energy absorbed by

commercial and vacant site surfaces would be overestimated by 0.9 and 8.1 x 10^9 J,

respectively.

Initial investigation into primary productivity of woody plants in the CAP-LTER

ecosystem showed that carbon dioxide assimilation was limited primarily by water

availability and secondarily by high temperature inhibition of photosynthesis during

summer months (Martin and Stabler, 2002). Plant carbon acquisition potential was

estimated to be 1.2 kg C m^{-2} of leaf surface area in irrigated urban landscapes. Based on

two dimensional plant canopy cover measured in the current study, plants at SFR sites

might potentially take up over 101.6 kg more carbon per year than do those in multi-

family residential (MFR) sites under conditions of similar water availability and

temperature. This number is likely greater when 3-dimensional leaf area index is

considered. Differences in C uptake might be further exacerbated by differences in

temperature associated with land cover characteristics of different land uses, and plant

respiration might also be affected by temperature, in general increasing by a Q_{10} value of

2.2 with temperature increase.

Land and vegetation cover characteristics of the urban desert ecosystem described

here will be used in subsequent chapters of this dissertation to offer explanations for

observed phenomenon and to make predictions about urban plant ecosystem function.

Although turf and herbaceous vegetation cover do represent a significant portion of land

cover and vegetation in SFR land uses, the primary focus of subsequent chapters will be

on woody vegetation.

Table 2.2. Mean albedo and range of values for urban surfaces from various sources[z], and calculated albedo for predominant land uses based on per cent cover by various surfaces.

Surface	Mean albedo (range)		Land Use	Calculated albedo
Asphalt	0.075	(0.05-0.10)	Commercial	0.173
Concrete	0.200	(0.15-0.35)	Industrial	0.220
Gravel	0.300	(0.20-0.40)	Institutional	0.197
Metal	0.575	(0.40-0.75)	MFR	0.224
Soil (desert)	0.165	(0.15-0.18)	Recreational	0.250
Tar roof	0.125	(0.10-0.15)	SFR	0.220
Tile roof	0.225	(0.10-0.35)	Transportation	0.150
Vegetation (grass)	0.270	(0.24-0.30)	Vacant	0.332
Water (low sun)	0.650	(0.50-0.80)	Water	0.190
Water (high sun)	0.040	(0.03-0.05)		

[z]Sailor (1998); Campbell and Norman (1998); Environmental Protection Agency (2003).

CHAPTER 3: URBAN MICROCLIMATES WERE RELATED TO LAND USE AND VEGETATION INDEX

Summary

   Recent trends in planning for sustainable urban development stress the importance of incorporating climate knowledge in decision making processes.   Urban sprawl and conversion of agricultural and natural lands to urban and suburban uses creates a heterogeneous patchwork mosaic of pervious soil and vegetation and built impervious surfaces such as asphalt, glass and concrete.   Land use influences relative cover by vegetation and anthropogenic surfaces and resultant microclimates influence human comfort, air quality, energy consumption, and urban ecosystem processes. To elucidate how heterogeneity of land use might affect microclimate, early morning and afternoon near surface temperatures and humidities were measured at 160-m (0.1 mile) intervals along multiple transects in the Phoenix, Arizona, USA, metropolitan and outlying areas during June and December 1999.   A Landsat thematic mapper normalized differential vegetation index (NDVI) image of the Phoenix area was used to examine spatial patterns of vegetation cover. In addition, microclimate and NDVI data collected during 1975-6 along two transects were compared to those collected during 1999 to determine if temporal changes in land use and NDVI affected microclimates. During 1999, greatest disparity in microclimate as a function of land use occurred during pre dawn summer hours. Agricultural and residential land uses had the highest relative humidities, dew point temperatures, and NDVI with lowest air temperatures.   Commercial land uses and industrial areas had highest temperatures and lowest NDVI. Temperatures were

generally negatively correlated to NDVI (r =–0.32 to –0.78), while humidities and dew

point temperatures were generally positively correlated to NDVI (r= 0.22 to 0.77).

Distance from the urban core of Phoenix did not affect NDVI but had a significant effect

on adjusted air temperature (r =-0.63). Comparison of data collected during 1975-6 and

1999 showed general decreases in NDVI and relative increases in temperature along both

transects.   The patterns of the relationship between microclimate and NDVI and

evaluation of statistical analyses suggest that urban microclimates in Phoenix, Arizona

are a function of the interactive effects of vegetation cover and some other independent

variable, likely land cover by other, non-vegetative urban surfaces. Temporal changes in

NDVI and air temperature suggest that planned urban greening might be useful to help

offset loss of agricultural lands and reduce expansion of the urban heat island in Phoenix.

Introduction

The urban heat island effect is a well documented phenomenon and the need to

incorporate knowledge of urban climatology in planning for urban growth has been

acknowledged (de Schiller and Evans, 1996; Thamm, et al., 1999; Eliasson, 2000). Built

surfaces such as asphalt and concrete absorb, store, and reradiate more thermal energy

per unit area than do the vegetation and soil typical of rural and undisturbed landscapes.

In cities, alterations in hydrology due to loss of pervious surface area increase runoff and

reduce soil water storage capacity, reducing evaporative cooling of the air. Vegetation

retained or added to developed areas reduces these effects through shading and

evapotranspiration, and use of vegetation to ameliorate urban heating is one strategy that

has generated significant interest (Simpson and McPherson, 1998; Sailor, 1998; Jo and McPherson, 2001).

The relative cover of vegetation and anthropogenic surfaces influences urban climate at several scales. Mesoscale, urban boundary layer climates reflect the combined influence of often heterogeneous microclimates within the urban canopy layer (UCL) (Schmid and Oke, 1990). Within the UCL, trees and buildings existing singly or in clusters create strong spatial variability in microscale processes such as shading, mechanical turbulence, and advection, up to a distance of several kilometers (Oke, 1989). Although UCL scale is of interest to planners because it most affects human comfort, heterogeneity of microclimate might also affect ecosystem process such as microbial breakdown of nutrients and plant and animal physiological processes (Clergeau and Simonnet, 1996; Pouyat, et al., 1997; Van-Rensburg, et al., 1997).

Vegetation cover might have the greatest impact on urban microclimates in hot, arid regions with mild winters, due to effects of irrigation enhanced evapotranspiration during dry summer seasons and continuous metabolic activity of plants throughout the year (Avissar, 1996; Sailor, 1998). The metropolitan area of Phoenix, Arizona is situated in the Sonoran Desert in the southwestern United States. Diversion of water from the Salt and Colorado Rivers for agricultural and urban landscapes has created expanses of vegetation much denser than would otherwise exist in this arid region. In Phoenix, where virtually all managed landscape vegetation is irrigated, evapotranspiration might be expected to especially influence urban microclimates relative to less arid areas where supplemental water is not added to the landscape. A survey conducted in the Phoenix metropolitan area of 200 randomly chosen 30m x 30m sites showed that land cover by

surfaces such as asphalt, concrete or soil, as well as plant canopy area, was a function of socioeconomic land use (Chapter 2). Although the urban heat island effect has been well-documented in the Phoenix area (Brazel, et al., 2000), the classic urban to rural increase in vegetation cover typical of most urban forests (Miller, 1997) does not apply there, where urban vegetation density is greater than in the surrounding desert (Martin and Stabler, 2002).

The purpose of this study was to examine spatial patterns of urban and suburban canopy layer microclimate and vegetation in the Phoenix metropolitan area, a mixed desert, agricultural, and urban area of nearly 3 million people and covering more than 3000 km^2. Because Phoenix is in a desert and subject to arid climatic conditions, it was hypothesized that 1) spatial heterogeneity in temperature and atmospheric moisture would be related to land use; 2) land use would influence vegetation cover; 3) vegetation cover and associated latent heat flux would be the most important factor influencing microclimates; and 4) that changes in spatial patterns of land use and vegetation cover over time would influence urban microclimates. To test these hypotheses, four transects within the Phoenix metropolitan area, chosen to represent a broad range of land use and to include both the urban core and urban fringe, were evaluated for spatial patterns of microclimate conditions, land use, and vegetation index. In addition, historical NDVI and microclimate data from two transects were used to evaluate how land use conversion affected NDVI and microclimate.

Methods

Transect selection and land use evaluation

Four transects over generally flat topography were selected to cover the geographic

range of the greater Phoenix metropolitan area, to include heterogeneous patterns of land

use, to evaluate both the urban core and the urban fringe, and to include areas previously

studied and currently in land use transition for ongoing studies. Figure 3.1 shows a map

of the Phoenix metropolitan area with coarse scale land use/land cover characterization

(Stefanov, et al., 2001) and the locations of each transect.

Transects 1 and 2 were chosen to repeat work conducted by Brazel and Johnson

(1976). The northern half of transect 1 is an area of mixed commercial and residential

land uses that was developed prior to 1976, while the southern half was predominantly

agricultural land during 1976 but has since been developed into residential and

commercial land uses.   The eastern portion of transect 2 lies within the Pima Indian

Reservation and has remained agricultural and unchanged since 1976, while the western

portion has remained mixed commercial and residential. Transect 3 consists of the urban

core to the south and a mature, densely vegetated, flood-irrigated residential area to the

north. Transect 4 is marked by heterogeneity, transition, and the urban desert interface.

Land use classification data obtained from the Maricopa Association of

Governments proved outdated and unreliable, so evaluation of land use was based on

socioeconomic use and function of structures present, degree of site development, and

observed human activity visible from of the transect center (American Planning

Association, 2000). Land use on each transect was categorized in 161-m (0.1 mile)

increments because the Phoenix area is laid out in gridded blocks defined by main street

intersections at 1609-m (1 mile) intervals, and while some heterogeneity exists at the 1-mile scale, land use within a developed block tends to be consistent.   When no single land use category could be applied to a segment due to heterogeneity, it was classified as mixed.

Details of land and vegetation cover were not evaluated from the ground for transects due to impracticality of undertaking such a task for over 600, 161-m segments. Preliminary research via a survey of 200 sites in the Phoenix metropolitan area showed that land use affected land and vegetation covers, but that building and tree heights were similar across land uses (Chapter 2). In that study, mean building height was only 5.6-m and mean tree height only 4.4-m, so sky view factors were not considered important to this metropolitan area characterized more by horizontal sprawl and small trees than by vertical skyscrapers or remnant forests.

Microclimate parameters

Along each transect, near surface temperature (T) and relative humidity (RH) measurements were made at approximately 161 m (0.1-mile) intervals to capture multiple measurements within a land use classification using a moving vehicle outfitted with meteorological sensors. Measurements were made from approximately 0500 to 0630 HR (pre-dawn) and 1500 to 1630 HR on days of clear, calm (windless) anticyclonic conditions during June and December 1999. For transect 2, data were also collected at 2200 HR during March 1999 for comparison to data collected there during March 1976.

T was measured with two shielded copper constantan thermocouples positioned in front of the moving vehicle at 0.5 m above ground. RH and T were measured with a
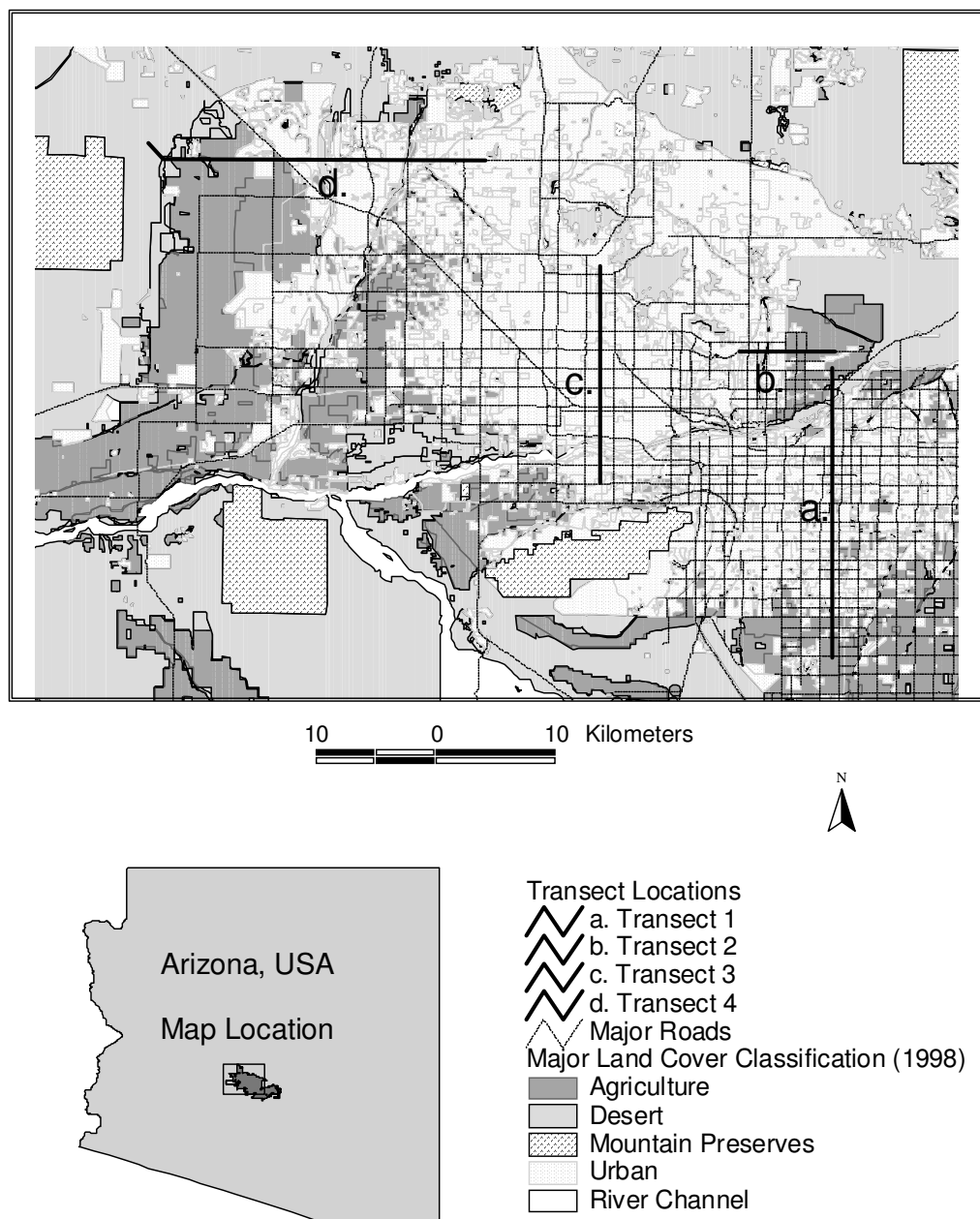
Figure 3.1 Map of the CAP-LTER study area showing main land cover classification

and location of transects evaluated for microclimate and NDVI

HMP 45C temperature and relative humidity probe (Campbell Scientific' Logan, Utah)

positioned over the moving vehicle 2.0 m above ground. From these data, dew point

temperatures (Td) were calculated. Reported T is the mean of the three temperature

measurements.   Measurements were recorded every 12 sec using a 21X micrologger

(Campbell Scientific, Logan, Utah).

   Each transect was run at least twice, traveling in opposite directions, and means for

each 0.1 mile spatial increment along each transect were calculated to reduce the effects

of temporal changes in microclimate which may have occurred during the course of each

run.   Iterations of measurements were numbered and recorded on detailed maps of each

transect at the time of data collection, and data recorded during periods when the vehicle

was stopped at traffic lights were removed from the analysis. Voice recordings were also

made to confirm the exact location of each microclimate data point. The asphalt road

was a surface common to all transects, eliminating differences in effects associated with

land cover immediately below the sensors for each land use.

Vegetation index

   Vegetation index along each transect was evaluated using a normalized difference

vegetation index (NDVI) map produced from a Landsat thematic mapper (TM) image of

the Phoenix area (spheroid Clark 1866, zone 12, Datum NAD27, georeferenced to UTM),

taken in April 1998, approximately 14 months prior to collection of microclimate data.

The NDVI image was obtained from researchers evaluating the spatial and temporal

distribution of land cover in the Phoenix urban area (Stefanov, et al., 2001). The spatial

resolution of the image was 28.5 m (0.018 mi) per pixel. All NDVI data were converted

from metric units of distance to miles to conform to land use classifications.

To accurately locate each transect on the NDVI images, the map coordinates of the

beginning and end of each transect were determined using a standard topographical and

quadrangular map of the Phoenix metropolitan area (scale of 1:250,000), with crosshairs

corresponding to USGS 15-minute maps (Delorme mapping, 1993). Based on those

coordinates, areas of interest (AOI) were created using ERDAS Imagine® software with

transect widths of 20 Landstat TM pixels (570 m), with the road defining the transect at

its central axis. The 20 pixels associated with transect width was selected based on the

height of T and RH sensors at 0.5 to 2.0 m; most of the footprint of land influencing

fluxes at that height range is expected to be within 20 to 450 m of the sensors (Burba,

2001).

Historical comparison

Microclimate data were collected via similar car-mounted apparati along transects 1

and 2 during June 1976 and March 1975, respectively. For that study, air temperature

was measured at approximately 1 m above the ground for both transects, and atmospheric

moisture was measured using a thermister psychometric system on transect 1. For

complete report of the analyses of the land use and microclimate data collected during

1976, see Brazel and Johnson (1980). Microclimate data from that study used for the

current analysis were those collected along transect 1 at 0500 during June 1976 and along

transect 2 at 2200 during March 1976. NDVI values along transects 1 and 2 were

calculated from a 1975 Landsat TM image produced by Stefanov, et al. as described previously for the 1998 NDVI data.

Regional scale climatic conditions for the appropriate sampling periods during 1976 and 1999 are shown in Table 3.1. During the two June microclimate sampling dates for transect 1, synoptic scale conditions of temperature and atmospheric moisture were similar during 1976 and 1999. Synoptic scale conditions differed slightly during the sampling dates for transect 2 during March of 1976 and 1999. Mean daily temperature and sea level pressure were somewhat lower during the 1976 sampling period, while relative humidity was similar. Wind direction varied for both historical comparison dates, but wind speed was low for all.

Statistical analyses

For each transect, analysis of variance (ANOVA) was conducted for the 1998-9 data using a general linear model procedure (PC SAS, version 6.03, Cary, NC) with land use as the independent treatment variable and T, RH, Td, and NDVI as response variables. Type IV sums of squares were evaluated to account for unequal sample sizes for vegetation indices and microclimate observations for each land use. Duncan's multiple range tests were employed to compare treatment means, with an $\alpha = 0.05$ level of significance.

Pearson correlation coefficients were calculated to measure degree of association between vegetation and microclimate parameters using a regression model with NDVI as the independent variable and T, RH, or Td as the dependent variable. Residuals of Type IV sums of squares for each observation of the dependent variables were plotted against

Table 3.1. Mean daily values of air temperature in °C (T), sea level pressure in mbs
(SLP), specific humidity in g/kg (SH), % relative humidity (RH), geopotential height of
the 500 mb surface in m (GPH) and wind direction (W) interpolated from synoptic
mapping for microclimate sampling dates during March and June of 1976 and 1999.

	T	SLP	SH	RH	GPH	W
March 1976	11	1017	0.006	50	5600	W
March 1999	15	1015	0.006	50	5650	N
June 1976	27	1011	0.004	20	5825	S
June 1999	26	1011	0.004	23	5775	NE

the dependent variables to check model assumptions and look for significant statistical patterns. In addition, all temperature data collected during June 1999 pre dawn runs were pooled and adjusted to a reference temperature for the appropriate date and time at Sky Harbor Airport. Regression analysis of NDVI and adjusted temperature (Ta) and T within each transect as a function of distance from the urban core (D) was conducted to detect urban to rural gradients for NDVI and/or temperature. Due to lack of a consistent and reliable reference station, no statistical comparisons between the 1975-6 and 1999 data were made, and only patterns are discussed within the context of this study.

Results

Land use effects on microclimate

Land use affected microclimate parameters in all transects during most data collection periods (P > F 0.01, Tables 3.2-3.3). In general, variation in microclimate parameters as a function of land use was greatest during pre-dawn summer hours. During this sampling period, the greatest effect was seen along transect 1, where near surface T in commercial land uses was on average 8.5°C higher than in agricultural land uses (Table 2) and near surface RH and Td were 16.2% and 5.9°C, respectively, higher in agricultural than in commercial land uses (Table 3.2). The least variation in microclimate parameters as a function of land use occurred during the December afternoon data collection period, when maximum difference in T and Td as a function of land use was less than 2° and 4° C, respectively, and maximum difference in RH was less than 5% (Table 3.3). For each transect, land use effects on microclimate were generally greater during pre-dawn hours than during afternoon hours in both June and December.

35

Table 3.2. Effects of land use on early morning (0500 HR) and afternoon (1500 HR) temperature in °C along 5 transects in Phoenix, Arizona, USA during June 1999.

	0500			1500		
	T	RH	Td	T	RH	Td
Transect 1						
Commercial	21.5 a	17.5 d	-4.8 d	35.7 a	6.0 b	-7.4 b
Residential	20.8 ab	19.1 d	-3.9 d	35.5 ab	6.4 b	-6.8 b
Industrial	20.2 bc	18.7 d	-4.7 d	34.8 c	6.7 b	-6.7 b
Mixed	18.0 cd	24.9 c	-1.8 c	35.4 ab	6.1 b	-7.5 b
Vacant	17.5 d	30.9 b	0.0 b	35.2 b	6.4 b	-6.9 b
Agricultural	13.0 e	33.7 a	1.1 a	35.3 b	7.8 a	-4.9 a
Transect 2						
Commercial	22.6 a	25.4 c	0.7 c	36.1 a	9.4 b	-1.2 b
Residential	21.1 b	31.2 b	2.5 b	35.9 a	9.6 ab	-1.0 ab
Recreational	21.1 b	33.6 ab	4.3 a	36.2 a	10.1 a	-0.2 a
Fallow Agricultural	17.9 c	36.0 a	2.4 b	35.4 b	9.9 ab	-0.9 ab

Table 3.2 (continued). Effects of land use on early morning (0500 HR) and afternoon (1500 HR) temperature in °C along 5 transects in Phoenix, Arizona, USA during June 1999.

Transect 3

Commercial	30.0 a	22.1 b	6.0 b	41.6 a	8.8 b	2.1 b
Industrial	29.8 a	21.2 b	5.7 b	41.7 a	8.6 b	1.7 b
Residential	7.8 b	27.4 b	7.4 a	40.9 b	10.1 a	3.4 a

Transect 4

Commercial	27.2 a	35.3 a	10.2 a	41.0 a	10.0 a	3.0 a
Vacant	25.8 b	35.8 a	9.3 b	40.8 a	8.6 b	0.8 b
Residential	25.7 b	35.2 a	9.0 b	41.0 a	9.5 ab	2.2 a
Agricultural	25.2 c	28.7 b	5.3 d	40.3 b	8.6 b	0.5 b
Mixed	24.8 c	35.3 a	8.0 c	40.4 b	8.6 b	0.7 b
Desert	24.8 c	35.3 a	8.0 c	40.5 b	7.3 c	-1.5 c

z Values are treatment means (n range 6 to 320) and those followed by the same letter within a column are not statistically different at α= 0.05 by Duncan's Multiple Range Test for each transect.

Table3.3. Effects of land use on early morning (0500 HR) and afternoon (1500 HR) temperature in °C along 4 transects in Phoenix, Arizona, USA during Decmeber 1999.

	0500			1500		
	T	RH	Td	T	RH	Td
Transect 1						
Industrial	8.5 a	36.8 b	-9.2 c	18.2 c	12.0 a	-12.0 a
Commercial	7.1 ab	41.4 a	-8.3 ab	19.2 a	11.5 b	-12.0 a
Residential	6.0 abc	42.3 a	-8.1 a	18.9 ab	11.5 b	-12.1 ab
Mixed	4.3 bc	41.9 a	-8.6 b	19.1 a	11.3 b	-12.4 ab
Vacant	2.9 c	40.9 a	-9.8 d	19.1 a	10.8 c	-13.1 c
Agricultural	2.6 c	41.4 a	-9.5 cd	18.6 bc	11.3 b	-12.5 b
Transect 2						
Commercial	5.1 a	33.8 b	-9.5 b	17.4 a	13.4 b	-10.9 b
Recreational	4.7 a	39.0 a	-8.1 a	17.3 a	15.9 a	-8.8 a
Residential	4.0 b	37.2 a	-9.3 b	17.3 a	13.4 b	-11.0 b
Fallow Agricultural	3.1 c	33.9 b	-11.3 c	17.3 a	12.5 c	-11.9 c

Table 3.3 (continued). Effects of land use on early morning (0500 HR) and afternoon (1500 HR) temperature in °C along 4 transects in Phoenix, Arizona, USA during Decmeber 1999. Note that data were not collected along transect 4 during December.

Transect 3						
Industrial	7.3 a	40.4 b	-5.3 b	22.3 a	12.4 b	-8.1 b
Commercial	6.9 a	42.8 b	-5.0 b	22.0 a	13.0 b	-7.7 ab
Residential	4.9 b	56.6 a	-3.1 a	21.6 b	13.9 a	-7.2 a
Transect 4						
Commercial	7.9 a	19.0 d	-14.3 a	18.4 a	12.0 bc	-11.5 a
Residential	6.3 b	20.8 c	-14.9 b	18.3 a	12.0 bc	-11.5 a
Vacant	6.0 b	21.2 c	-14.7 ab	18.2 a	11.8 c	-11.8 bc
Desert	3.8 c	23.1 b	-15.5 c	17.5 b	12.2 b	-12.0 c
Mixed	3.0 c	25.3 a	-15.1 b	17.5 b	12.6 a	-11.6 ab
Agricultural	1.7 d	26.1 a	-15.7 c	17.4 b	12.5 a	-11.9 c

[z] Values are treatment means (n range 6 to 320) and those followed by the same letter within a column are not statistically different at α= 0.05 by Duncan's Multiple Range Test for each transect.

Land use effects on vegetation index

Land use affected NDVI in all transects (P > F 0.01, Table 3.4). The range of NDVI

for all transects was from 0.506 in the dry river bottom, to 0.665 in a recreational, flood

control greenbelt with a golf course and small lakes. Commercial land uses had NDVI

values that ranged from 0.533 to 0.541, residential from 0.541 to 0.619, and agricultural

from 0.534 (fallow) to 0.656 (active). The greatest range of NDVI within a single

transect occurred along the shortest, with a low value of 0.534 and a high of 0.665 on

transect 2.

Correlation of vegetation index to microclimate

Pearson's correlation coefficients between NDVI and all microclimate parameters

were significant for most transects during the summer morning sampling period (P > F

0.01, Table 5) with one exception. For transect 2, neither T nor RH were correlated to

NDVI. Correlations were significant for transect 3 during all sampling periods. In

general, T was negatively correlated to NDVI (r=-0.32 to –0.78) during the pre dawn

hours in both summer and winter except for transect 2 where there was no significant

relationship. This relationship was more variable for afternoon measurements but was

negative when significant (r=-0.32 to –0.54). With one exception, RH and Td were

positively correlated to NDVI when significant (r=0.22 to 0.79). Transect 4 showed the

one exception with a negative correlation between Td and NDVI during the summer

morning sampling period. The greatest correlation between microclimate parameters and

NDVI occurred on transect 3 when pre-dawn, summer microclimate data were analyzed

Table 3.4. Effect of land use on normalized differential vegetation index (NDVI)

	NDVI
Transect 1	
Agricultural	0.617 a
Mixed	0.575 b
Vacant	0.573 b
Residential	0.572 b
Commercial	0.537 c
Industrial	0.525 c
Transect 2	
Recreational	0.665 a
Residential	0.552 b
Commercial	0.541 bc
Fallow Agricultural	0.534 c
Transect 3	
Residential	0.619 a
Commercial	0.541 b
Industrial	0.506 c
Transect 4	
Agricultural	0.622 a
Mixed	0.558 b
Residential	0.541 c
Desert	0.539 c
Vacant	0.533 c
Commercial	0.533 c

[z] Values are treatment means (n range 6 to 320) and those followed by the same letter within a column are not statistically different at $\alpha= 0.05$ by Duncan's Multiple Range Test for each transect

Table 3.5. Pearson's correlation coefficients (r-values) showing the degree of associations between early morning (0500 HR) and afternoon (1500 HR) microclimate parameters and normalized differential vegetation index (NDVI) along 5 transects in Phoenix, Arizona, USA during June and December 1999.

| | Summer | | | | Winter | | | |
| | 0500 HR | | 1500 HR | | 0500 HR | | 1500 HR | |
	r-value	P>F	r-value	P>F	r-value	P>F	r-value	P>F
Transect 1								
Temperature	-0.54	0.01	0.01	0.87	-0.43	0.01	-0.01	0.95
Relative Humidity	0.58	0.01	0.02	0.82	0.22	0.01	0.26	0.01
Dewpoint	0.57	0.01	-0.02	0.78	-0.11	0.20	-0.01	0.98
Transect 2								
Temperature	0.05	0.75	0.14	0.40	0.13	0.42	-0.08	0.63
Relative Humidity	0.25	0.10	-0.09	0.58	0.40	0.01	0.79	0.01
Dewpoint	0.58	0.01	-0.01	0.97	0.48	0.01	0.76	0.01

Table 3.5 (continued). Pearson's correlation coefficients (r-values) showing the degree of associations between early morning (0500 HR) and afternoon (1500 HR) microclimate parameters and normalized differential vegetation index (NDVI) along 5 transects in Phoenix, Arizona, USA during June and December 1999.

Transect 3								
Temperature	-0.78	0.01	-0.54	0.01	-0.65	0.01	-0.34	0.01
Relative Humidity	0.77	0.01	0.69	0.01	0.72	0.01	0.54	001
Dewpoint	0.67	0.01	0.62	0.01	0.72	0.01	0.48	0.01
Transect 4								
Temperature	-0.37	0.01	-0.33	0.01	-0.44	0.01	-0.32	0.01
Relative Humidity	-0.12	0.11	-0.08	0.30	0.44	0.01	0.46	0.01
Dewpoint	-0.32	0.01	-0.13	0.09	-0.05	0.53	0.15	0.04

by mile, yielding positive correlation between Td and NDVI as high as 0.98 (data not shown).

Plots of pre-dawn summer residuals of each microclimate parameter against the dependent variable showed distinct and consistent patterns for all transects and for residuals of pooled Ta data plotted against Ta when NDVI was used as the independent variable (figure 3.2). Neither numerical transformation of the data nor alterations of the regression model eliminated the pattern seen in the residual plots. This pattern is suggestive of some independent variable missing from the regression model (Gomez and Gomez, 1984.)

Urban to Rural Gradients

Regression of pooled NDVI on D indicated a very weak relationship ($r^2 = 0.003$, P>F =0.001, data not shown), suggesting lack of an urban to rural vegetation gradient in Phoenix. Pre-dawn summer Ta was significantly and negatively correlated to D (figure 3.3). Within each transect, pre-dawn summer T was significantly negatively correlated to D, ranging from an r value of -0.51 near the urban core (transect 3) to -0.97 at the urban fringe (transect 4), confirming an urban heat island effect unrelated to vegetation cover. Multivariate regression of Ta on D and NDVI yielded a significant r^2 value of 0.49 (P>F 0.001).

Historical comparison

In general, NDVI decreased and temperature increased on both transects 1 and 2 between the 1975-6 and 1998-9 study periods (figure 3.4). For transect 1, conversion of

44
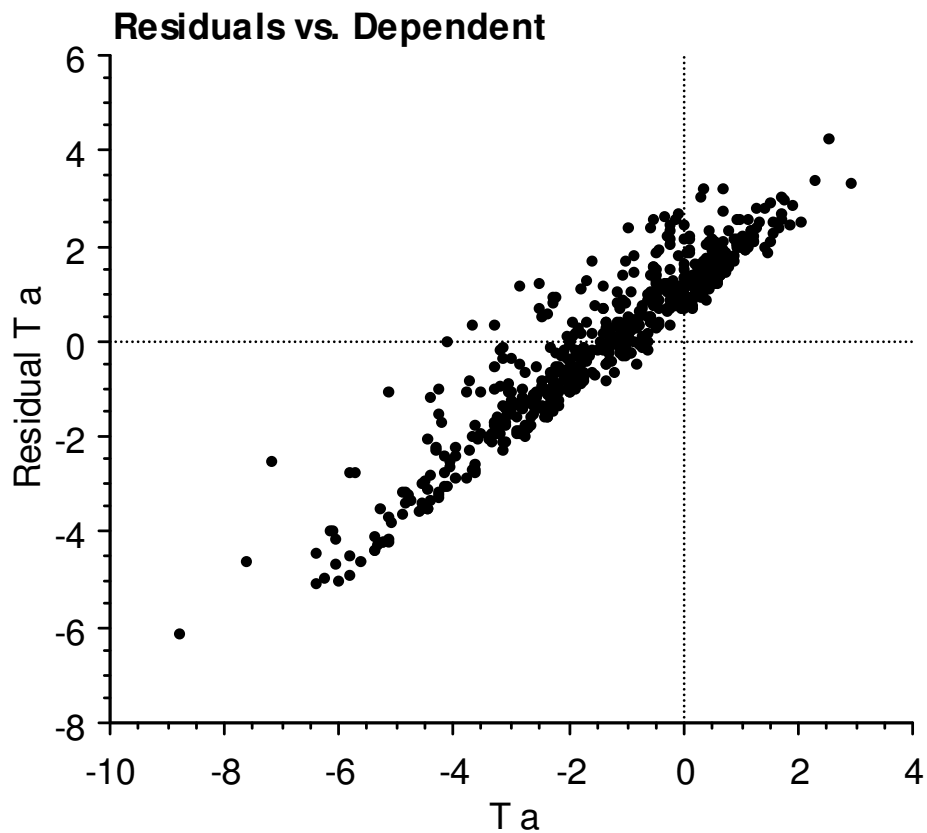
Figure 3.2. Plots of residuals of for each observation of adjusted temperature (Ta)

plotted against the dependent variable Ta for a regression model using NDVI as the

independent variable for all transects combined.
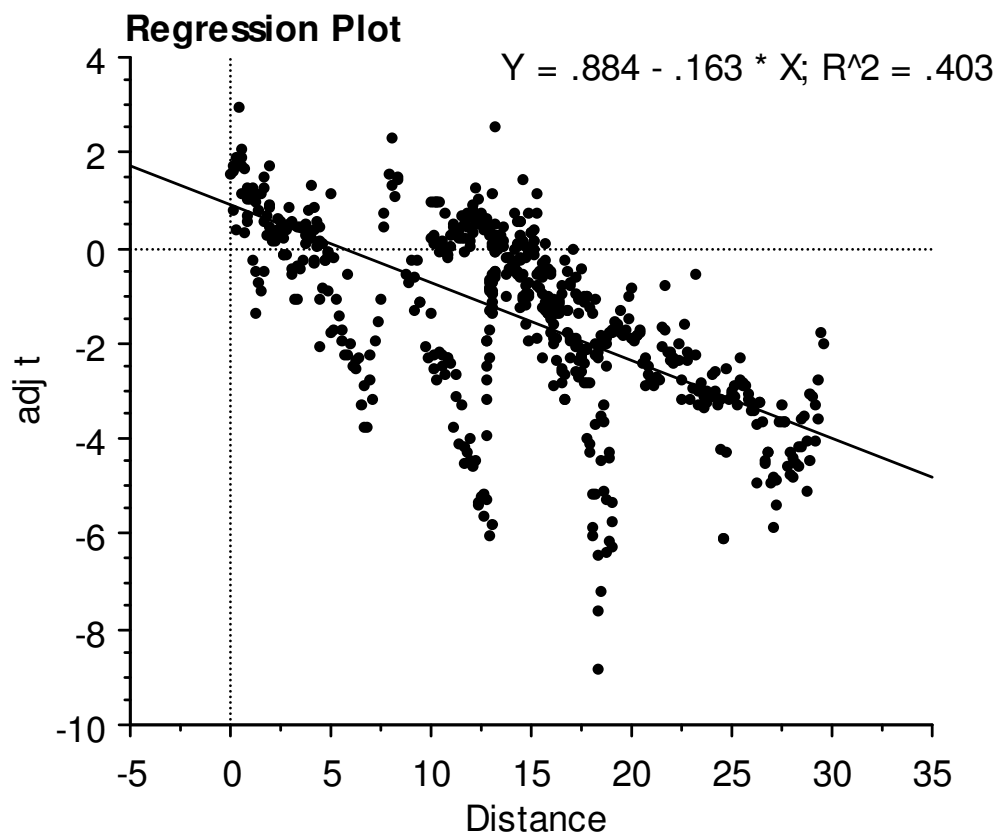
Figure 3.3. Plot of regression of adjusted air temperature (Ta) as the response variable

and distance from the urban core as the independent variable using pooled data from all

transects.
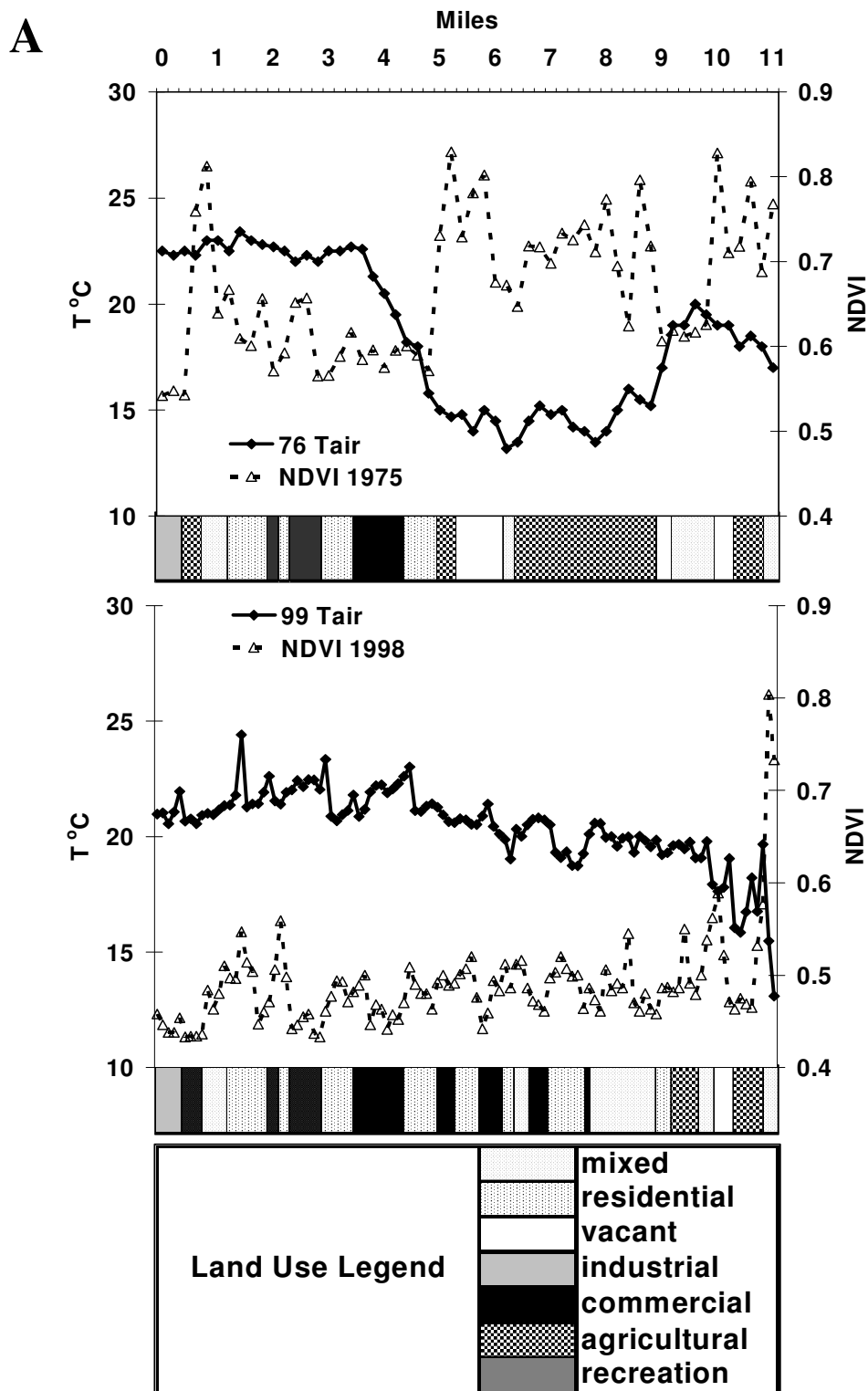
Figure 3.4. (A) Plots of land use, air temperature (T) and normalized differential vegetation index (NDVI) along transect 1 during 1976 and 1999.

B
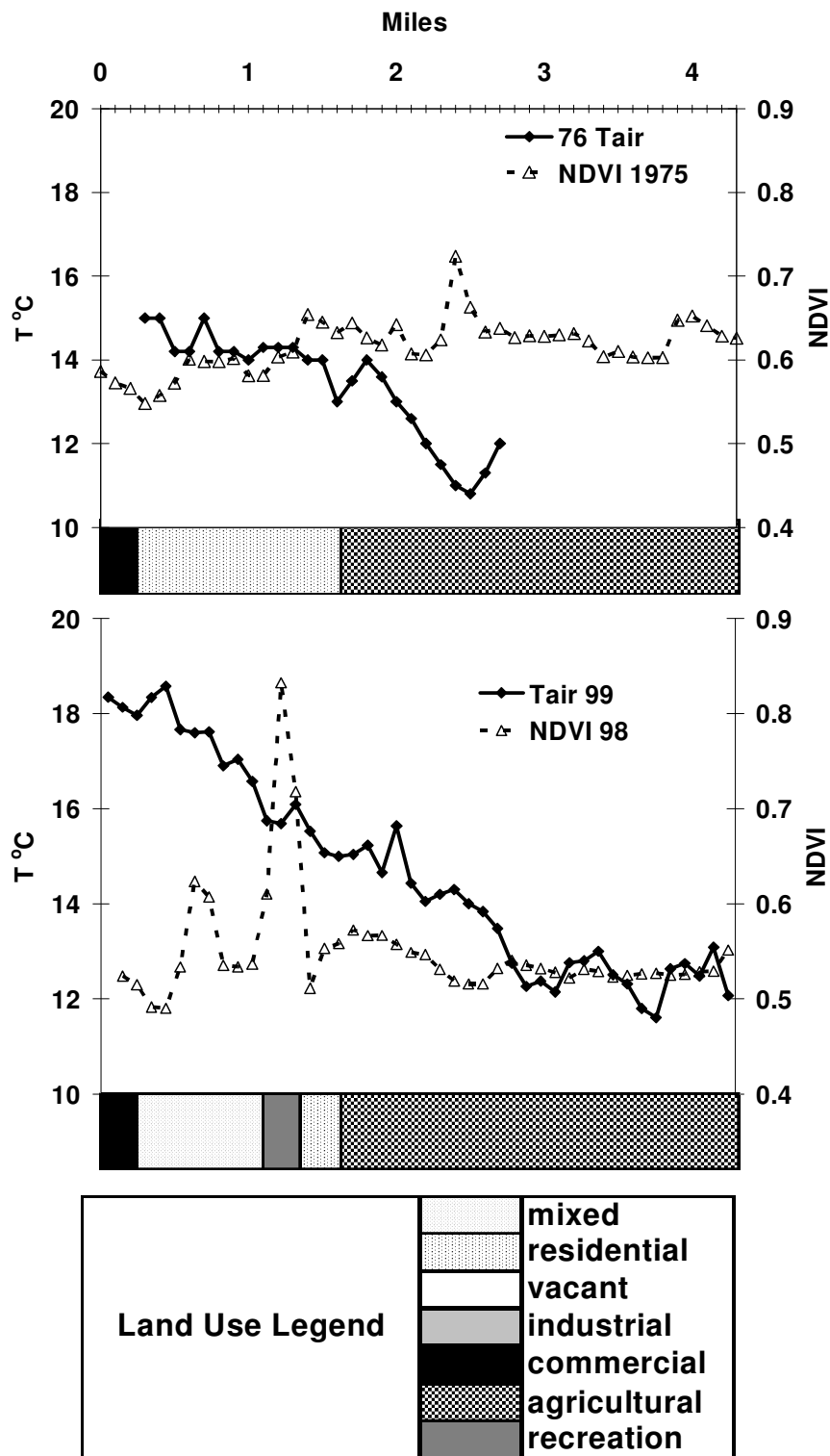
Figure 3.4. (B) Plots of land use, air temperature (T) and normalized differential vegetation index (NDVI) along transect 2 during 1975 and 1999.

vacant and agricultural lands to residential and commercial uses reduced a steep

temperature gradient that was observed in 1976. Within transect 2 land use changed

relatively little between 1975 and 1999, while the temperature gradient between

developed and agricultural areas increased slightly.   Conversion of a dry wash to a

greenbelt flood control area increased NDVI considerably in that segment of transect 2,

but that conversion did not appear to influence the general trend toward increased

temperature.

Discussion

Microclimate patterns in the Phoenix area were related to land use in this study,

particularly during pre dawn summer conditions when heat storage by the urban fabric

might be expected to most influence energy balance. As in other arid, low elevation, mid

latitude continental cities, summer in Phoenix is characterized by strong daytime

radiational loading potential, which is manifest as increased night time low temperatures

associated with the urban heat island effect. During the afternoon hours, even though air

temperatures are highest and latent heat flux associated with vegetation might be

expected to most affect microclimates, increased atmospheric mixing likely decreased

those affects at the scale at which our measurements were taken.

Vegetation also influenced urban microclimates. The atypical patterns in the NDVI

microclimate relationship during 1999 for transects 2 and 4 can likely be attributed to the

temporal disparity between the NDVI image that was available for analysis, taken in

April 1998, and collection of the microclimate data during 1999. The western portion of

transect 4 was at the urban fringe in an area of rapid development during 1998-99 (figure

3.1). Areas there that were active agricultural lands during April 1998 had been displaced by suburban development or were in transition during June and December 1999. The eastern portion of transect 2 was comprised almost exclusively of cotton fields which were fallow when the NDVI image was taken during April 1998 but active during June 1999 when microclimate data were collected.

The pattern of the relationships between NDVI and various microclimate parameters, coupled with analyses of residuals of the dependent microclimate variables, suggest that microclimate conditions in the Phoenix metropolitan area were a function of interactive effects of vegetation cover and some other independent variable, probably land cover by non-vegetation surfaces related to degree of urbanization near the urban core. The residuals plots (figure 3.2) showed that at high T_a, the regression model tended to underestimate T_a as a function of NDVI, and overestimate it at low T_a, suggesting that some other factor is contributing in a predictable pattern to variation in air temperature.

Results from this study show that vegetation cover influenced microclimate in the Phoenix area, and supports use of vegetation augmentation to reduce urban heating. Although land use did influence NDVI and microclimate, land cover is probably an attribute more relevant to biophysical process in urban ecosystems and what most needs to be addressed in the planning process. The data presented provide evidence for a heterogeneous patchwork of microclimates related to socioeconomic land use and vegetation cover, as well as an urban to rural decrease in temperature not associated with vegetation cover. The data are less supportive of the hypothesis that vegetation cover and latent heat flux are the primary determinants of microclimate in the Phoenix urban

ecosystem, but instead suggest that interactive effects of vegetation and other land cover

associated with urbanization are most important.   More intensive evaluation of the

effects of relative land cover by soil, vegetation, and anthropogenic surfaces on urban

microclimates is needed to make predictions and incorporate these considerations into the

planning process.

CHAPTER 4: PLANT CARBON AND WATER DYNAMICS OF IN RESPONSE TO LANDSCAPE MAINTENANCE REGIMES

Summary

The ecology of plants in cities is poorly understood relative to natural and agroecosystems, and heterogeneous management of urban plants should be considered when making predictions about urban ecosystem processes. Total above ground productivity (PP), average canopy leaf area (LA) and irrigation water use efficiency (WUE_I) of experimental plots similar to suburban residential sites were determined in response to a two by four factorial treatment combination of drip irrigation rates, low (ca. 800 L m^{-2} yr^{-1}) or high (ca. 1950 L m^{-2} yr^{-1}), and shrub pruning regimes (two taxa hedged every six weeks or six months; renewal pruned yearly, or unpruned control). WUE_I was defined as PP per 1000 L of water applied over 3 years. Measures of instantaneous leaf gas exchange were scaled to the whole plant and plot level and integrated over time to estimate maximum plot carbon acquisition (CAP) and transpiration potentials (TP) and elucidate how plant physiological processes influenced observed patterns of PP and WUE_I. Mass sap flow of *Nerium oleander* was monitored to compare methodologies for estimating transpiration. On a whole plot basis, PP and LA were highest and WUE_I was lowest after 3 years under high irrigation rates. Plot LA was higher in plots with shrubs pruned every six months or left unpruned relative to plots with shrubs pruned every six weeks or pruned yearly. For the two pruned shrub species, *Nerium oleander* and *Leucophyllum frutescen*s, WUE_I was affected similarly by interaction of irrigation and pruning treatments, while affects on PP and LA differed between the two taxa. Mean

instantaneous plant gas exchange fluxes were higher under high irrigation rate and in all

pruning treatments relative to plots with shrubs left unpruned.   Instantaneous

transpiration efficiency (ITE, the ratio of CO_2 assimilation to transpiration) was lowest

under high irrigation rate relative to low rate and in plots with shrubs pruned every 6

weeks relative to other pruning treatments. Scaling and integration of gas exchange data

and resultant comparisons to measures of PP and WUE_I indicated that plant carbon

uptake and transpiration potentials were a function of water availability and LA and that

irrigation and pruning practices might be managed to improve landscape WUE_I.

Abbreviations

A CO_2 assimilation (μmol m^{-2} s^{-1})

CAP   maximum carbon acquisition potential (kg)

E   transpiration (mmol m^{-2} s^{-1})

gs   stomatal conductance (mmol m^{-2} s^{-1})

GW   green waste (removed biomass) kg

IA   irrigation application volume (L)

IAE   irrigation application efficiency (TP/IA)

ITE   instantaneous transpiration efficiency (A/E)

LA   average canopy leaf area (m^2)

LAI   leaf area index

PP   above ground productivity (kg)

TC   total plot fixed carbon (kg)

TP   maximum transpiration potential (L)

WUE   water use efficiency (biomass/transpiration)

$WUEI_I$ irrigation water use efficiency (kg PP/ 1000 L irrigation)

Introduction

Urban ecosystems represent intermediate areas of land use intensity and management relative to highly manipulated agricultural systems and relatively unmanaged natural areas (Sukopp, 1990). Field studies conducted in the metropolitan area of Phoenix, Arizona, USA, during 1998-99 indicate that on a leaf area basis, a variety of C3 plants in irrigated residential sites had carbon assimilation fluxes 1.6 times lower than plants in agricultural sites and 2.8 times higher than those in unirrigated, remnant Sonoran Desert sites within the city (Martin and Stabler, 2002). In that study, while water availability most affected plant productivity, management practices such as irrigation application rate varied tremendously between urban residential sites, the predominant land use in the Phoenix metropolitan area (Chapter 2).

Urban environments can adversely affect water balance in plants (Whitlow and Basuk, 1988; Kjelgren and Montague, 1997; Kjelgren et al., 2000). In many cities supplemental irrigation is used to maintain plant aesthetic quality because of limited water storage capacity imposed by impervious surfaces and root- restricted settings, increased evapotranspiration due to hotter urban microclimates, or in regions with seasonal low precipitation. In arid zone cities such as Phoenix, most urban landscape plantings are irrigated, and it is estimated that amenity landscape plantings can account for 30-50% of municipal water use in the desert southwestern United States (Kjelgren et al., 2000).

Stomata control the carbon-water balance of plants by acting as antiportals for diffusive CO_2 uptake and water vapor loss (Farquhar and Sharkey, 1982). In undisturbed desert systems, primary productivity (PP) of C3 plants is most limited by water

availability (Szarek and Woodhouse, 1977; Szarek and Woodhouse, 1978), probably due to stomatal closure and subsequent reduction in diffusive CO_2 assimilation (A) (Martin and Stabler, 2002). Instantaneous transpiration efficiency (ITE) has been defined as the ratio of A to transpiration (E) fluxes, and contributes to whole plant water use efficiency (WUE), which is often defined as biomass accumulation per unit of water transpired (Eamus, 1991). Under well-watered and supra-optimal temperature conditions, ITE and WUE can be reduced because as stomatal conductance (gs) increases, A becomes limited by other factors such as light driven electron transport while E increases linearly with gs, causing ITE to decrease rapidly (Buckley, et al. 1999). Phoenix's urban plant community includes many arid zone, exotic and native species, but there is probably no advantage for vegetation that is adapted to desert conditions of rapid evaporation and sporadic water supplies to reduce water loss via stomatal closure in irrigated landscapes.

Above ground space for plants in urban landscapes is often limited by buildings, roadways and power lines, and supplemental irrigation of drought-adapted plants encourages rapid growth that can quickly obstruct view lines, walkways and roads. Many urban plants are regularly pruned under various regimes because of overcrowding, failure to consider mature plant size relative to location, and human preferences for plant appearance. The landscaping guidelines set forth by the city of Mesa, Arizona, state that "all shrubs, hedges, and shaped trees shall be trimmed monthly in a manner that creates a neat and well-cared-for appearance" (Donna DiFrancesco, City of Mesa, personal communication). While some data can be found in the literature reviewing the affects of pruning on productivity in agroforestry systems, it is unknown to what degree shrub pruning practices affect urban plant gas exchange, PP, or WUE. When shrubs are

frequently hedged, source tissue for photosynthate is constantly being removed and replaced by new growth, representing a significant carbon sink. Biomass of pruned plant material represents C removed from the plant storage pool and in many urban areas disposal of this so called green waste (GW) via mulching or land fill is a growing concern and expense (Lucy Bradley, Maricopa Cooperative Extension, personal communication).

It was hypothesized in this experiment that irrigation and pruning of desert adapted shrubs would impact landscape plant carbon acquisition (CAP) and transpiration potentials (TP), which in turn would influence landscape productivity (PP) and water use efficiency (WUE) due to effects of those practices on leaf level gas exchange fluxes and source sink relationships. Data presented here convey results from a three year study of plant productivity and water cycling in experimental plots designed to resemble single family residential plots in number and life forms of plants present.

Methods

Site description and plant materials

The experimental site was comprised of fourteen 10-m x 10-m plots. During May 1999, each plot was planted with trees, shrubs, and ground covers to based on the number and life forms of vegetation in "xeric style" residential landscape plots surveyed in the Phoenix metropolitan area (Martin and Stabler, 2002). A 2.5-m wide strip of unvegetated soil was maintained between each plot. Each 100-m^2 plot was divided into equal quadrants and planted with one each of 19-L container grown *Eucalyptus microtheca* F. Muell. 'Blue Ghost" (coolibah) and *Quercus virginiana* var. *fusiformis*

(Small) Sarg. (Texas live oak) in opposite corner quadrants. Six each of 3.8-L container-grown clones of *Nerium oleander* L. 'Sister Agnes' (oleander) and *Leucophyllum frutescens* var. green cloud™ Berl. (Texas sage) spaced approximately 1.5 m on center and grouped in opposite diagonal quadrants of the plot were installed in the remaining two quadrants. *Rosmarinus officinalis* L 'Prostratus" (prostrate rosemary) was used as a ground cover and one each of 3.8L clones were planted in each plot near the center in the quadrant occupied by *L. frutescens* (figure 4.1A).

     Eucalyptus microtheca is indigenous to the arid and semi-arid regions of Australia. It is a fast growing, drought-adapted ever green tree that is widely used in lower desert California and Arizona landscape plantings for screening and shade. The dense, isobilateral leaves of *E. microtheca* have lignified epidermal cells that are desiccation resistant. *Eucalyptus* species occurred at 6% of urban sites surveyed in the CAP-LTER 200 site survey (Chapter 2).

     Quercus virginiana var. *fusiformis* is typically locally evergreen, but may be partially or wholly deciduous in cold winters. *Q. virginiana* var. fusiformis is native to seasonally moist regions of Texas and Chihuahua, Mexico and is used in low desert landscape plantings because of its heat and drought tolerance and slow growth rate. No *Quercus* species were reported at sites in the CAP-LTER 200 site survey.

     Nerium oleander is an upright and rounded evergreen shrub in the family Apocynaceae and is native to the Mediterranean region. *Nerium* leaves are persistent and sclerophyllous and drought adaptations include waxy, glabrous leaves with encrypted stomata on the lower epidermis only. The cultivar *'Sister Agnes'* usually produces copious clusters of white flowers from April until September and can grow from 3 to 6 m

in height with similar spread. Because of its mature height and spread, it is an accent

landscape shrub that is often renewal pruned or hedged in urban settings. In the CAP-

LTER 200 site survey, *Nerium* occurred at 29% of the urban sites surveyed (Chapter 2).

 Leucophyllum frutescens var. green cloud[TM] is a medium to large shrub, mounding

up to 3.5 m in height and as wide when water is plentiful. The variety green cloud[TM] is an

accent shrub that produces magenta flowers from April until November. It is native to the

Chihuahuan Desert and is partially winter deciduous in natural ecosystems. Leaves are

grayish green, tomentose and ephemeral and drought tolerance in natural ecosystems is

often associated with drought deciduousness and rapid regeneration of tissue when water

becomes available. Several species of similar *Leucophyllum* species (*L. candidum*, *L.

laevigatum*, and several cultivars of *L. frutescens*) are commonly planted and hedged or

renewal pruned in the Phoenix metropolitan area and the genus occurred in 21% of urban

sites surveyed there.

 Rosmarinus officinalis L. 'Prostratus' prostrate (rosemary) is an aromatic, evergreen

Mediterranean shrub with a low spreading habit generally less than 1 m in height to 3 m

spread. Leaves are narrow and sclerophyllous with trichomes and a thick adaxial cuticle.

R. officinalis is well adapted for growth in hot climates and alkaline soils and is

biologically active during the cool winter months. *R. officinalis* occurred at 7% of sites

surveyed in Phoenix. (all plant descriptions form the L.H. Bailey Hortorium, 1976).

 To facilitate establishment, plants in all plots were drip irrigated at a similar rate (416

L m^{-2} yr^{-1}) for the first six months after transplanting. To reduce effects of possible soil

A

NORTH

H :high irrigation rate

L :low irrigation rate

1Y : yearly renewal pruning

6m : hedged every 6 months

6w : hedged every 6 weeks

C : unpruned control

E: Eucalyptus microtheca

L: Leucophyllum frutescens

N: Nerium oleander

Q: Quercus virginiana

R: Rosmarinus officinalis

**Each plot is 10m x 10m
3 m separate each plot**

88 m N/S

23 m E/W

B
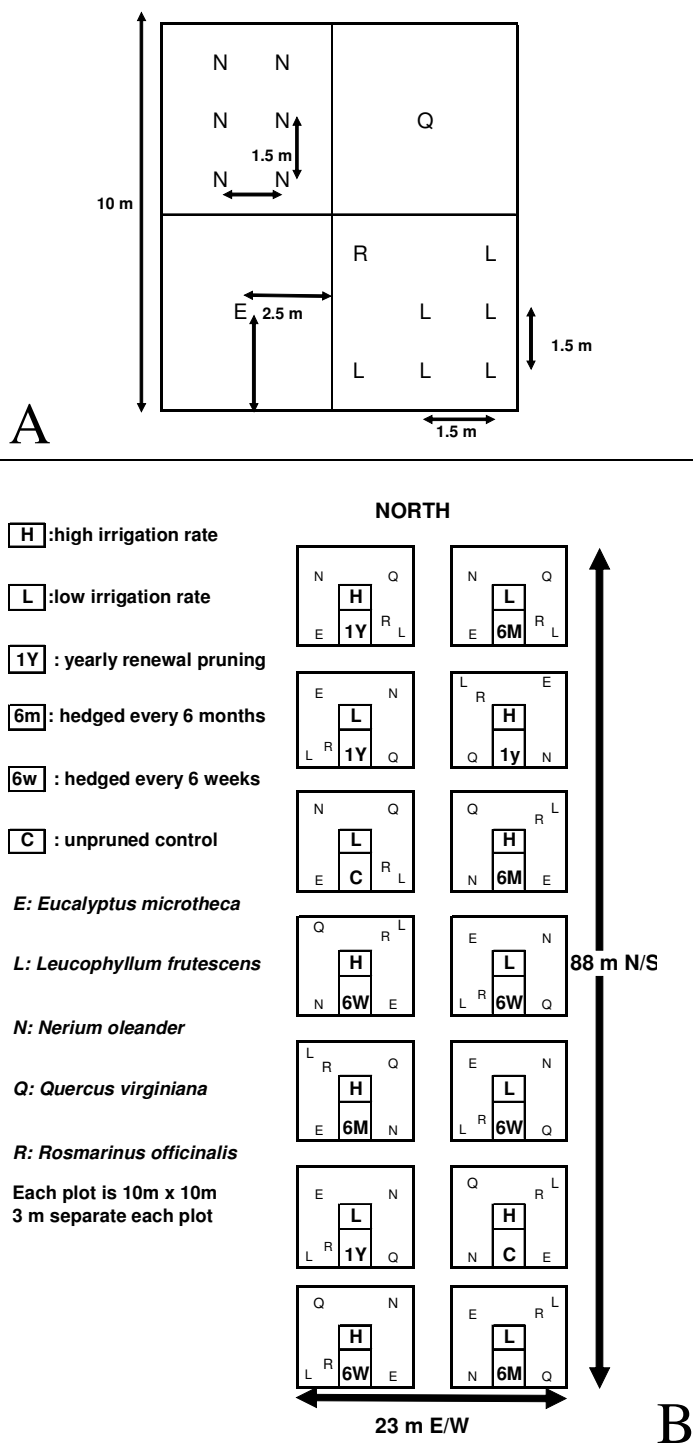
Figure 4.1. (A) Arrangement of *Nerium* (N), *Quercus* (Q), *Eucaluptus* (E), *Rosmarinus* (R) and *Leucophyllum* (L) within a 100 m^2 plot and *(B)* site layout showing experimental design with high (H) and low (L) irrigation rate and shrub pruning treatments and the position of each taxon within the plots (see key above).

nutrient heterogeneity, all plants were fertilized initially and subsequently each April

with controlled release fertilizer 20N-4.4P-4K plus micronutrients (Best Paks™, J.R.

Simplot Co, Boise, Idaho).

Experimental design

   Beginning January 2000, plots were subjected to a two by four factorial treatment

combination of drip irrigation rate and shrub pruning regime for 3 years. Irrigation

treatments were defined as low rate (mean 814 L m^{-2} yr^{-1}) and high rate (mean 1954 L

m^{-2} yr^{-1}). Pruning treatments included hedging *Nerium* and *Leucophyllum* every 6 weeks

or 6 months, yearly renewal pruning those taxa to the ground, or leaving them unpruned.

Irrigation treatments were blocked in seven rows of two plots, one of each irrigation rate

treatment, running in a north to south direction, with the four shrub pruning treatments

randomly assigned to entire plots within that scheme (figure 4.1B).

   Water was delivered by an automatic irrigation system to each plant through drip

emitters situated under the canopy near the base of each shrub or ground cover and under

the canopy near the trunk of each tree. During the first year, irrigation to tree species was

supplied by two 3.8 L hr^{-1} emitters each and to shrubs and ground covers by one 3.8 L

hr^{-1} emitter each. During the second year, the number of emitters supplying *Eucalyptus*

was increased to four, and during the third year to six. Also during the third year, the

number of emitters to *Quercus* was increased to three and to both shrub species was

increased to two.   The volume of water applied to each plot was monitored using

totalizing water meters (Precision Manufacturing Company, Orlando, Fla.). The volume

of irrigation to each plant was calculated as the total volume of water delivered to a plot

over time divided by the fraction of total emitters on the plot for each plant. The

irrigation rate was calculated as volume per m^2 of plot area per year. Irrigations were

scheduled to give plants in the high irrigation rate plots twice as much water as those in

the low rate irrigation rate plots and both were ramped seasonally. The irrigation rate

treatments were based on a previous assessment of landscape irrigation application rates

by local residents (Martin and Stabler, 2002). Precipitation was measured via tipping

bucket (Model TE525WS, Campbell Scientific, Ogden, Utah) and soil moisture content

was monitored at a depth of approximately 30 cm in unirrigated soil and for three

replicates of each irrigation rate treatment using soil moisture probes (ThetaProbe™,

Dynamax, Inc, Houston, Texas). Moisture probes were situated below the canopy near

the base of each of the two pruned shrubs species and approximately 1 m from the based

of *E. microtheca* . Precipitation and soil moisture data were recorded with a 23X

micrologger (Campbell Scientific). Mean annual soil moisture content (v/v) was 6.1,

12.9, and 16.7% for dry soil, low irrigation rate, and high irrigation rates, respectively

(figure 2).

For three years pruning treatments were applied to *N. oleander* and *L. frutescens* in

two plots for each irrigation treatment (4 plots x 3 pruning treatments). Shrubs were

either hedged every six weeks, hedged every six months during February and August or

renewal pruned to the ground yearly during February (n=2 plots and 12 pseudo replicates

of each shrub for each pruning treatment). In addition, shrubs in one plot within each

irrigation treatment were left unpruned as controls (n = 1 plot and 6 pseudo replicates of

each shrub species for each irrigation x pruning treatment combination). Trees canopies

were thinned and the base elevated yearly and similarly and *Rosmarinus* was left

unpruned on all plots.

PP, LA and WUE$_I$

The size of all plants was measured every three months. For trees, height, diameter,

canopy area and canopy base height were measured with a clinometer and steel tapes.

Tree canopy area was calculated as A = π (0.5 * ((NS + EW)/2))^2 where A is canopy

area, NS is the measured north/south dimension of canopy, and EW is the measured

east/west dimension of canopy, assuming a tree canopy to be circular with a radius of half

the average diameter.   Shrubs were also measured before and after each pruning event.

For shrubs and ground covers, canopy volume (height x width EW x width NS) was

measured. All pruned biomass and accumulated litter (green waste, GW) from each plant

was collected at pruning events, oven dried for 7 days at 70°C and weighed. Leaf surface

area to dry weight (DW) relationships were established using regression analysis by

measuring surface area of 100 leaves of each species using a digitizing camera system

interfaced to a computer and drying and recording mass after leaves were dried for 3 days

at 60°C (Appendix A). At the end of three years, all shrubs and ground covers were

pruned to the ground and fresh weight (FW) of all pruned material measured. All plants

with final FW < 2 kg were dried and weighed, as were all *Rosmarinus* and 3 replicates of

Nerium and Leucophyllum from each plot. The remaining *Nerium* and *Leucophyllum*

were sub-sampled and total DW was calculated based on FW/DW ratios of each plant.

Leaf material was separated
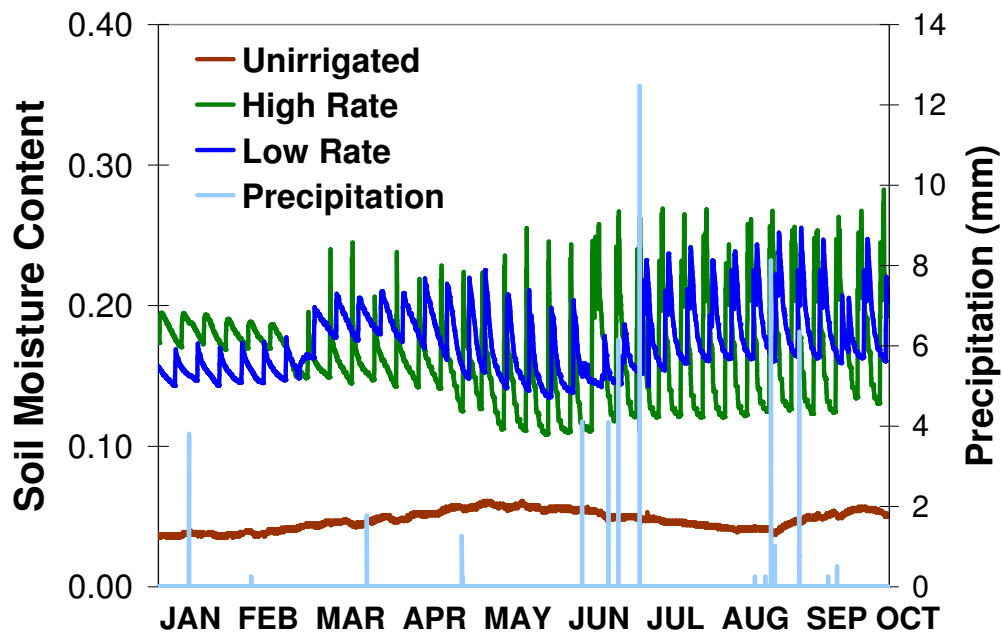
Figure 4.2. Representative patterns of precipitation (mm) and fraction soil moisture

content (v/v) under high rate, low rate, and unirrigated conditions.

from woody material of harvested plants and leaf DW was used to estimate final canopy

leaf area (LA) using the equations derived in Appendix A.

For *Eucalyptus,* standing biomass was estimated by the equation: $\log_e$ DW= -3.8604

+ 0.9644 $\log_e$ $(DBH^2$ x height) and LA was estimated via canopy area, assuming a leaf

area index (LAI) of 2.19 (Bell et al., 1985). Standing biomass of *Quercus* was

estimated using the equation: DW = -0.086 + 0.05 (d) where d is the trunk diameter at 15

cm and LA was calculated via canopy area assuming an LAI of 0.66 (Devitt et al., 1994).

Plot PP was calculated as the sum of estimated tree standing biomass and total biomass

removed via pruning and destructive harvest. Irrigation water use efficiency (WUE_I) was

calculated for each plant as PP per total volume of irrigation water applied for three

years. Precipitation was assumed to be equal to all plants and had negligible affect on

available soil moisture relative to irrigation (figure 2) so was not considered in WUE_I

calculations.

For trees, LA over time was estimated via measured canopy area and LAI.

Regressions of final LA on standing shrub canopy volume (Appendix B) were used to

estimate shrub LA over time. Average LA for each plant was calculated from all

measurements made during the 3 year study, and total plot average LA was the sum of

the average LA for all plants on a plot. Average LAI was calculated for the shrubs as

estimated LA/canopy area over three years.

For all treatment statistical comparisons of PP, LA, and WUE_I data, an analysis of

variance (ANOVA) was calculated using a general linear model procedure and Type IV

sums of squares (SAS version 6.03; SAS Institute, Cary, N.C.). Tukey's Studentized

Range Test was used to identify significant differences between variable responses to treatment effects, $P \leq 0.05$.

Plant gas exchange

On two consecutive days every 3 months from October 2000 until October 2002, maximum plant gas exchange fluxes were measured for the most recently physiologically mature plant tissues and consisted of partial leaves (*Nerium* and *Eucalyptus*), whole leaves (*Quercus*), or small shoot segments (*Leucophyllum* and *Rosmarinus*) of all plants. Measurements were made on cloudless days during a 3 hour time frame previously determined to be that of optimal conditions for maximum gas exchange fluxes for that season (Martin and Stabler, 2002). Measurements were made the day after a watering event for each irrigation treatment (two sampling days) to reflect fluxes under conditions of maximum water availability.

Measurements were made with a ¼-liter chamber connected to a portable infrared gas analyzer (Model LI 6250, LI-COR Inc., Lincoln, NE, USA) operated in closed system mode. The chamber thermocouple was positioned in direct contact with the abaxial surface of measured leaves and stems to measure shoot temperature. To reduce the potential errors associated with measuring plant gas exchange in an enclosed chamber, particularly with respect to leaf conductance (gs) and transpiration (E) as a measure of actual leaf gs and E under field conditions (Leuning and Foster, 1990; Rochette et al., 1990), a sampling protocol for gas exchange measurements that consisted of short measurement intervals (10-30 seconds) to minimize changes in the chamber microenvironment during the sampling interval, followed by exhaustion of the chamber

volume to return to ambient conditions, was employed. Typical chamber micro-

environmental conditions were as follows: initial CO_2 concentration ranged from 355 to

409 ppm and drawn down was less than 1 ppm per second; flow rate was adjusted to

maintain chamber relative humidity within 10% of ambient and for a given measurement

leaf to air temperature differential was $< 0.5^o$C. Instrument derived values for E

compared with values calculated from measured gs and vapor pressure deficit (VPD) via

the formula: E = gs * VPD/P, where P is local barometric pressure (McDermitt, 1990)

were similar via paired t-test, so instrument derived values for E were used for

subsequent scaling activities.

For each of the 9 seasonal 2-day sampling periods, 10 leaf or shoot replicate

measures for each irrigation x pruning interaction (n = 80 each species) of *Nerium* and

Leucophyllum and 20 replicate measures for each irrigation treatment (n=40 each species)

for other species were made. Total number of gas exchange measurements made for each

2-day seasonal sampling period was 280 except the first two measurement periods,

during which control plants and those pruned yearly were indistinguishable. For large

leaves, a known surface area was enclosed in the chamber and smaller leaves or shoot

segments were harvested and total one sided surface area was measured with a digitizing

camera system interfaced to a computer to calculate fluxes per unit leaf area.

For all statistical comparisons, an analysis of variance (ANOVA) was calculated

using a general linear model procedure and Type IV sums of squares (SAS version 6.03;

SAS Inst., Cary, NC). Tukey's Studentized Range Test was used to identify significant

differences between the mean responses to treatments, $P \leq 0.05$.

Scaling and integration of A and E

Total plant carbon acquisition potential (CAP) and transpiration potential (TP) were estimated as the maximum integral of A or E using trapezoidal numerical integration (Hornbeck, 1975; Martin and Stabler, 2002). Seasonal A and E data were used in conjunction with the model developed by Martin and Stabler to scale the amplitude of diurnal patterns of gas exchange fluxes to calculate daily CAP and TP. Formulae used in the calculation of daily CAP and TP are shown below. Equation 1 calculated CAP or TP from 0700 to 1600 HR, equation 2 from sunrise to 0700 HR, equation 3 from 1600 HR to sunset and equation 4 summated values calculated from equations 1-3 to estimate daily CAP or TP.

$$\int_{x1}^{X4} f(x)\,dx = \Delta x/2\,(f_1 + 2f_2 + 2f_3 + f_4) \tag{1}$$

$$\int_{x0}^{X1} f(x)\,dx = \Delta x/2\,(f_1) \tag{2}$$

$$\int_{x4}^{X5} f(x)\,dx = \Delta x/2\,(f_4) \tag{3}$$

$$\int_{x0}^{X5} f(x)\,dx = \int_{x0}^{x1} + \int_{x1}^{x4} + \int_{x4}^{x5} \tag{4}$$

where f_i equals the fraction of A_{max} or E_{max} at x_i, Δx equals a time interval between x_i and x_{i+1}, x_0 to x_5 = sunrise, 0700 HR, 1000 HR, 1300 HR, 1600 HR, and sunset, respectively.

Daily CAP and TP values were summated to estimate annual CAP or TP per unit leaf area.

To scale to the plot level, CAP and TP were calculated separately for each species and irrigation treatment, and for each irrigation x pruning combination for *Nerium* and *Leucophyllum*. Calculated values were multiplied by average LA for each species or interactive treatment combination for shrubs and summed for all plants on each plot for total plot CAP and TP for three years. The model for maximum CAP and TP assumes all leaves on a single plant to have similar conductance to CO_2 and water vapor and that light extinction and boundary layer decoupling are minimal within the context of the relatively open canopy of residential plots. Whole plot CAP and TP were calculated separately as a function of irrigation and pruning to incorporate differences in total plot LA and to compare to differences in whole plot PP and WUE_I.

To evaluate predictions of plot CAP in terms of observed plant productivity, estimates of total plot carbon fixed (TC) were made using PP data described above. Whole plot DW biomass was calculated as above ground PP added to estimated below ground mass, assuming an equal root-to-shoot (RS) ratio for all plants of 0.26 derived for upland woody vegetation (Cairns et al., 1997). Although pruning of shrubs will affect RS ratio immediately following a pruning event, changes in root and shoot biomass allocation to optimize source sink relationships and water and N dynamics might be expected to maintain long term RS ratios at a relatively consistent level (Chen and Reynolds, 1997; Gleeson, 1993). Total dry weight biomass was converted to biomass carbon by multiplying by 0.5 (Nowak and Crane, 2002). Estimates of whole plant respiration range from 40-60% of fixed C; given the high temperatures in the Sonoran

Desert, relatively high respiration rate was assumed such that biomass carbon represented only 40% of fixed C (Cannel and Thornley, 2000). TC for each treatment was therefore calculated as: (PP + (0.26PP)) x 1.25.

Mass sap flow in Nerium oleander

To evaluate predictions of TP, mass sap flow in *Nerium* was measured from May to October 2002 using constant power sap flow gauges (Dynamax Model SGA 13, Houston Texas) employing the heat balance method of Baker and Van Bavel (1987). This method involves applying a known quantity of heat to the stem, measuring directional fluxes of heat in the stem, and calculating sap flow rate as a residual in the heat balance equation. Stem-flow gauges were attached to *Nerium* stems of basal diameter 12-16 mm at least 2 cm above the soil surface on 4 plants within a single plot on two plots during any measurement time frame. Data were recorded continuously every 60 seconds and means output every 15 minutes using a portable micrologger (model 21X, Campbell Scientific). Thermal conductance for each gauge was determined during periods of assumed zero flow (pre-dawn) and final calculations of mass sap flow were made using FLOW32 software provided by Dynamax. Data were collected for at least one week per treatment to capture a full irrigation cycle, and for all pruning treatments low and high irrigation rate treatments were measured simultaneously. Simultaneous measurement of low and high volume control plants was not possible due to spatial constraints imposed by the plot layout.

On removing sap flow gauges, all leaves on the measured stem were removed and total leaf surface area measured using a digitizing camera interfaced to a computer. Total

hourly sap flow per unit leaf area for each measurement period was calculated as mean of

hourly flow in 4 plant replicates from each plot measured.   Total sap flow per unit leaf

per day was summed for each plant and scaled to the whole plant using regression

equations based on plant canopy volume (Appendix B) for total plant LA during the

measurement period, as described previously, and the mean of four replicates is reported.

Due to the temporal disparity in mass sap flow measurements in the various

treatment combinations and associated changing leaf to air VPD and irrigation

application volumes, no statistical comparisons of mass sap flow data were made and

only trends are discussed within the context of this work.

Results

PP, LA, and WUE$_I$ of individual taxa

Eucalyptus PP was highest under high irrigation rate, but WUE$_I$ and LA were not

affected. WUE$_I$ was lower in *Quercus* given high irrigation rate but PP and LA were not

affected. PP was highest in *Rosmarinus* at high irrigation rate but WUE$_I$ and LA were

unaffected (Table 4.1).

The two pruned shrubs species were affected differently by irrigation and pruning

treatments. For *Nerium,* irrigation and pruning affected PP but not interactively, while

both WUE$_I$ and LA were affected by treatment interaction (figures 4.3-4.5). *Nerium* PP

was 92% higher under high irrigation rate (figure 4.3A). *Leucophyllum* PP was affected

by treatment interaction such that at high irrigation rate, unpruned controls had PP that

was reduced up to 43% relative to pruned plants, and at low irrigation rate there was no

difference between pruning treatments (figure 4.3B).

The two pruned shrubs taxa showed similar interactive effects of irrigation and pruning on WUE$_I$ (figure 4.4A and B).   Shrubs given low rate irrigation and pruned yearly had highest WUE$_I$ for both species. At high irrigation rate, both taxa had the highest WUE$_I$ in plants pruned every 6 months. Average LA was affected interactively but differently for the two pruned taxa (figure 4.5A and B). *Nerium* had highest average LA when left unpruned at both irrigation rates, and plants pruned every 6 months did not differ from controls at high irrigation rate.   Highest average LA for *Leucophyllum* occurred in plants given high irrigation rate and pruned every 6 months. Lowest average LA occurred in plants pruned every 6 weeks for both taxa.

Whole plot PP, LA and WUE$_I$

Irrigation rate affected whole plot PP, LA and LAI, and WUE$_I$, while shrub pruning affected average LA and LAI on a whole plot basis but not GW or WUE$_I$ (Table 4.2). Irrigation had no affect on plot GW production or % PP removed as GW (GW %), while pruning influenced both. PP, LA and LAI were 92, 50, and 24% higher respectively and WUE$_I$ was 21% lower under high irrigation rate relative to low irrigation rate treatments. Plots in which the shrubs were left unpruned or hedged every 6 months had LA as much as 92% higher than plots with shrubs pruned every 6 weeks or yearly. LAI was highest in plots with shrubs hedged every 6 months. Total GW was lower in control plots relative to those with shrubs pruned yearly, but neither differed from plots with hedged shrubs. Only plots with hedged shrubs did not differ in terms of GW%.

Table 4.1. Effects of irrigation treatment on plant above ground biomass production (PP) in kg, irrigation water use efficiency (WUE$_I$, kg biomass/1000L water applied), and average canopy leaf area (LA) in m^2 in unpruned plant taxa for three years in experimental plots.

	PP	WUE$_I$	LA
Species			
E. microtheca			
High rate	[z]14.6a	0.56a	11.3a
Low rate	7.4b	0.67a	9.4a
Q. virginiana			
High rate	2.8a	0.17b	1.2a
Low rate	2.2a	0.33a	0.8a
R. officinalis			
High rate	2.15a	0.29a	0.4a
Low rate	0.96b	0.31a	0.3a

[z]Values are treatment means, n=7 for each species and irrigation treatment. Values followed by the same letter within a column for a treatment are not significantly different by Tukey's Studentized Range Test (P=0.05).
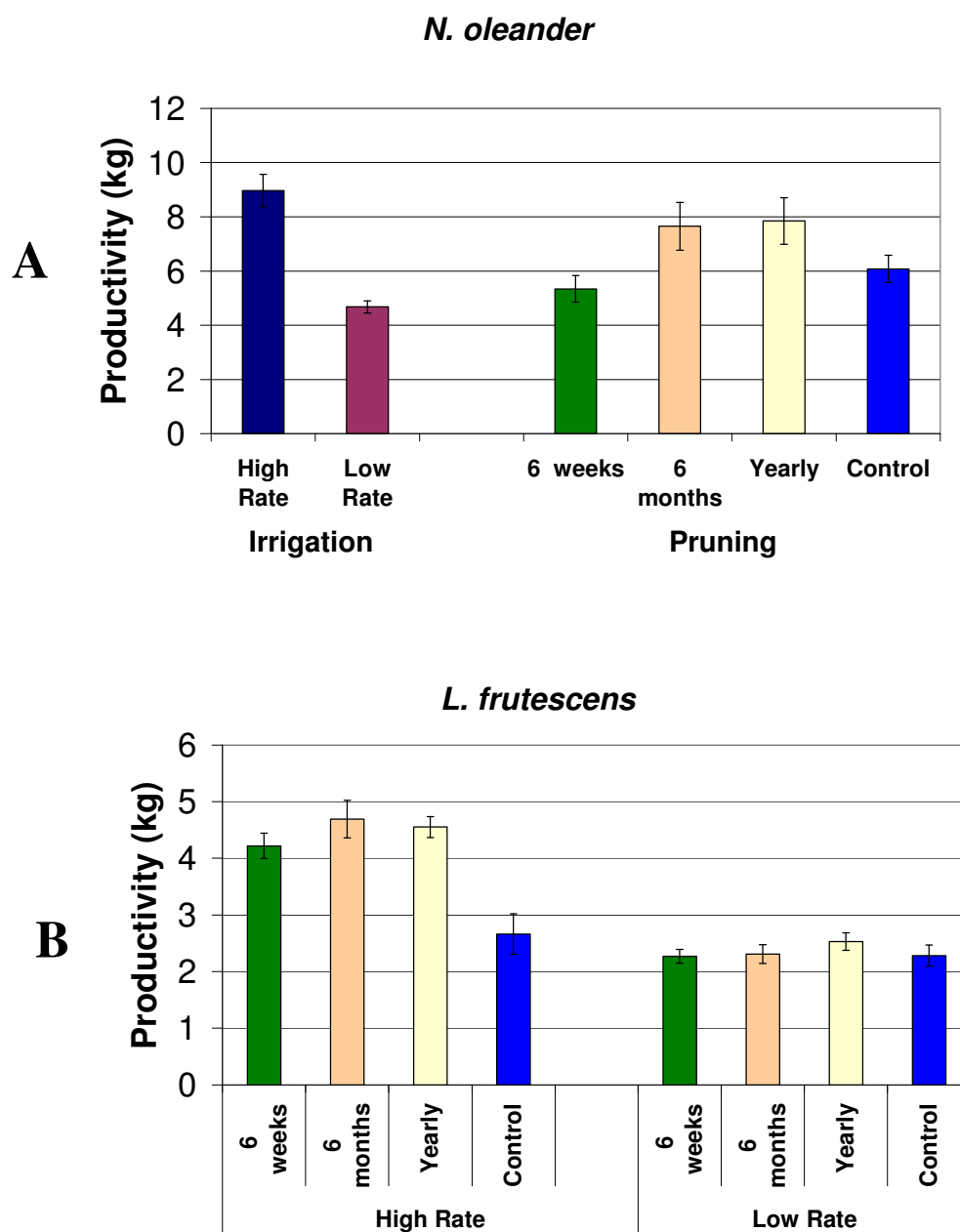
Figure

4.3. Effects of high or low irrigation rate and pruning regime (hedged every 6 weeks or 6 months, yearly renewal pruned, or unpruned controls) on above ground productivity in kg (PP) of (A) *Nerium oleander* and (B) *Leucophyllum frutescens*.
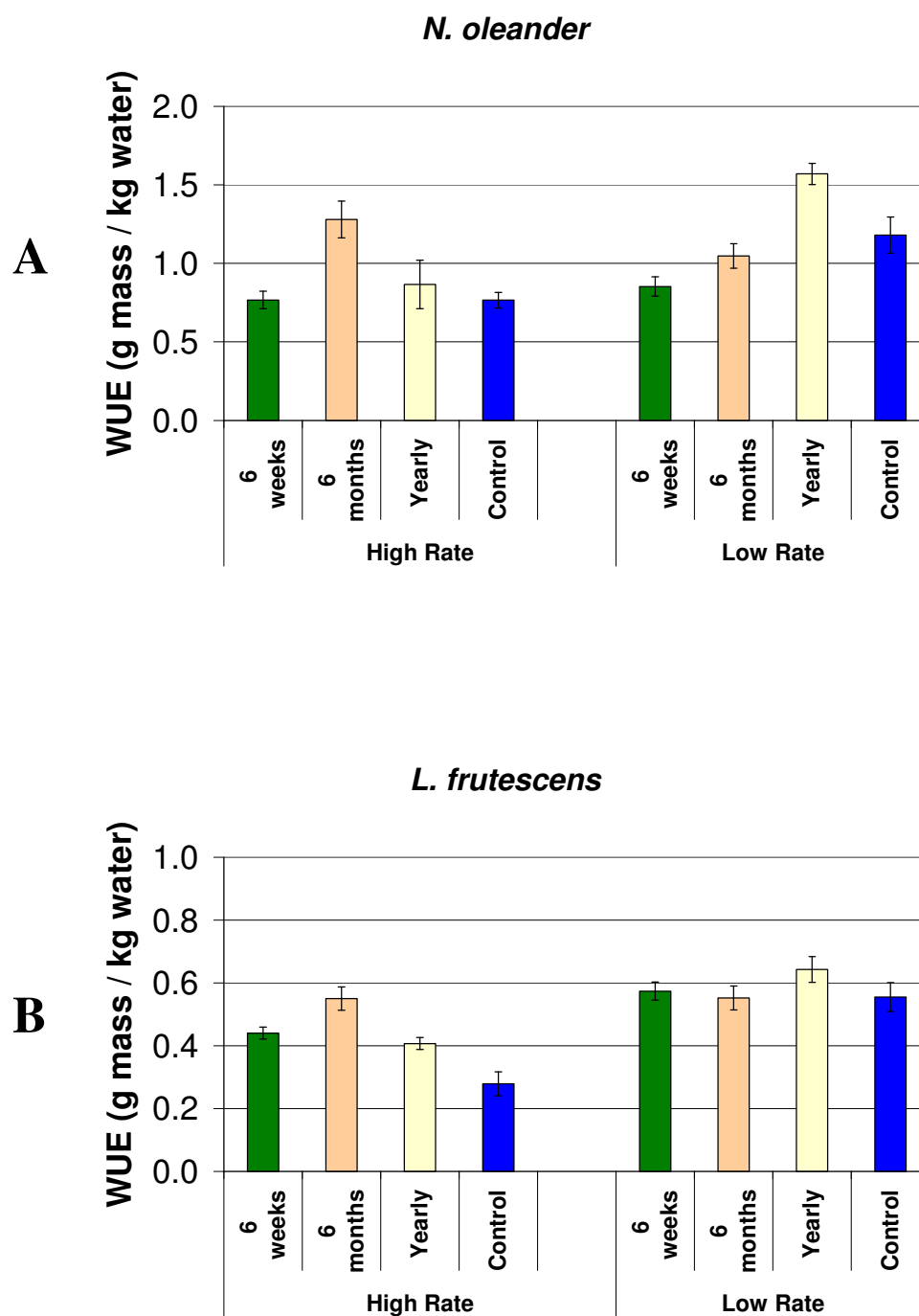
Figure 4.4. Effects of high or low irrigation rate and pruning regime (hedged every 6 weeks or 6 months, yearly renewal pruned, or unpruned controls) on irrigation water use efficiency (WUE$_I$, grams biomass/ kg water applied) of (A) *Nerium oleander* and (B) *Leucophyllum frutescens*.

N. oleander
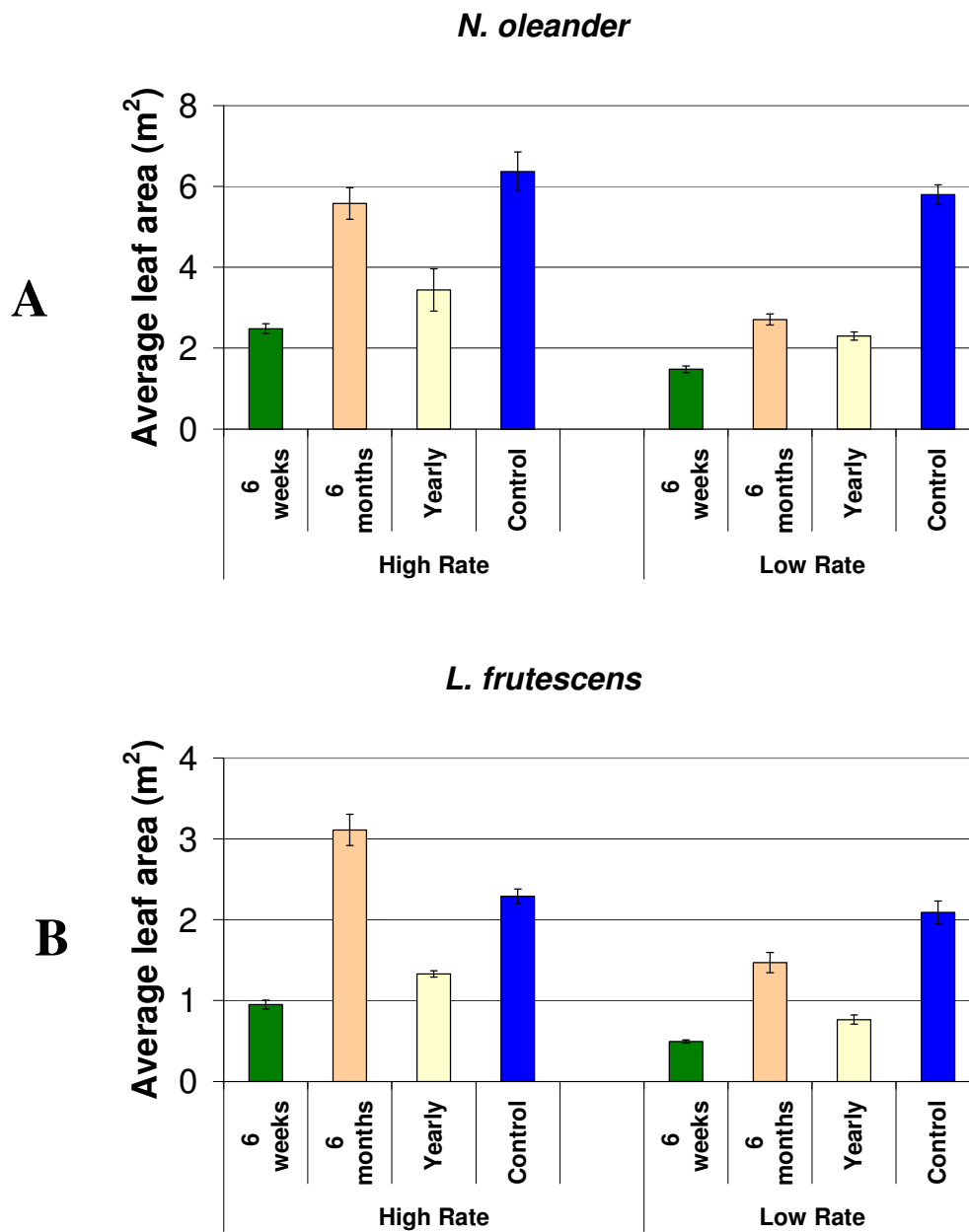
L. frutescens

Figure 4.5. Effects of high or low irrigation rate and pruning regime (hedged every 6 weeks or 6 months, yearly renewal pruned, or unpruned controls) on average canopy leaf area (LA) in m^2 in (A) *Nerium oleander* and (B) *Leucophyllum frutescens*.

Table 4.2. Total above ground whole plot biomass production (PP) and green waste (GW) in kg, per cent GW (%GW), irrigation water use efficiency (WUE$_I$, kg biomass/1000L water applied), average canopy leaf area (LA) in m^2, and average LAI as a function of high or low irrigation rate or pruning regime (shrubs hedged every 6 weeks or every 6 months, yearly renewal pruned, or unpruned controls) for three years in experimental plots.

	PP	GW	GW%	WUE$_I$	LA	LAI
Irrigation						
High rate	[z]98.7a	47.6a	46.0a	0.61b	49.2a	2.1a
Low rate	52.4b	25.2a	46.4a	0.79a	32.9b	1.7b
Shrub pruning						
6 week hedge	71.6a	26.5ab	37.4b	0.64a	28.3b	1.4b
6 month hedge	81.6a	34.2ab	41.0b	0.72a	50.1a	2.7a
Yearly renewal	80.1a	64.3a	79.4a	0.72a	33.8b	1.7b
Unpruned	62.2a	4.6b	7.5c	0.59a	63.3a	1.7b

[z]Values are treatment means, n=7 for each irrigation treatment, n= 4 for each pruning treatment and n=2 for unpruned control plots. Values followed by the same letter within a column for a treatment are not significantly different by Tukey's Studentized Range Test (P=0.05).

Plant gas exchange

To determine mean leaf level fluxes of A and E for experimental plots with mixed taxa, all gas exchange measurements collected over two years were pooled and classified according to plot irrigation and pruning treatments, season, and species. Values for instantaneous gas exchange fluxes per unit leaf area were calculated as the mean value for all 5 taxa without consideration of relative LA of taxa. Irrigation rate affected E, gs and ITE but not A of plants per unit leaf area (Table 4.3). E and gs were 7.7% and 6.3% higher, respectively, and ITE was 4.3% lower for plants in the high irrigation rate treatment relative to the low rate treatment. Higher instantaneous fluxes of A, E, and gs per unit leaf area were measured in plots in which shrubs were pruned relative to plots with unpruned shrubs, and those in which shrubs were pruned every six weeks had reduced ITE (Table 4.3). Pruning effects on mean whole plot gas exchange fluxes were the result of treatment effects on *Nerium* and *Leucophyllum* fluxes and were not manifest in unpruned species (data not shown).

Analysis of data by season showed highest fluxes of A for all plot irrigation and pruning treatments during spring, while E was highest during the fall sampling periods (figure 4.6). Under high irrigation rate, E increased between spring and summer, while gs decreased, while both E and gs decreased under low irrigation rate during that time period. Plants in control plots had the lowest fluxes of A, E, and gs throughout the year, and plots with shrubs pruned yearly showed the most variation in gas exchange fluxes (figure 4.7). Plots in which shrubs were renewal pruned in February had highest gas exchange fluxes during the spring and summer, but decreased in the fall relative to other

Table 4.3. Mean leaf fluxes of CO_2 assimilation (A, $\mu mol\ m^{-2}s^{-1}$), transpiration (E, $mmolm^{-2}s^{-2}$), stomatal conductance (gs, $mmolm^{-2}s^{-1}$) and instantaneous transpiration efficiency (ITE, A/E) from combined data for 5 plant taxa as a function of plot irrigation rate (high or low rate) or shrub pruning regime (shrubs hedged every 6 weeks or every 6 months, yearly renewal pruned, or unpruned controls) for three years in experimental plots.

	A	E	gs	ITE
Irrigation				
High rate	[z]10.5a	5.6a	186a	2.26b
Low rate	10.1a	5.2b	174b	2.36a
Pruning				
6 week hedge	10.4a	5.8a	187a	1.79b
6 month hedge	10.7a	5.5a	192a	1.94a
Yearly renewal	10.9a	5.7a	185a	1.91a
Unpruned	8.8b	4.4b	152b	2.00a

[z]Values are treatment means, n=1022 for each irrigation treatment, n= 584 for each pruning treatment and n=292 for unpruned control plots. Values followed by the same letter within a column for a treatment are not significantly different by Tukey's Studentized Range Test (P=0.05).
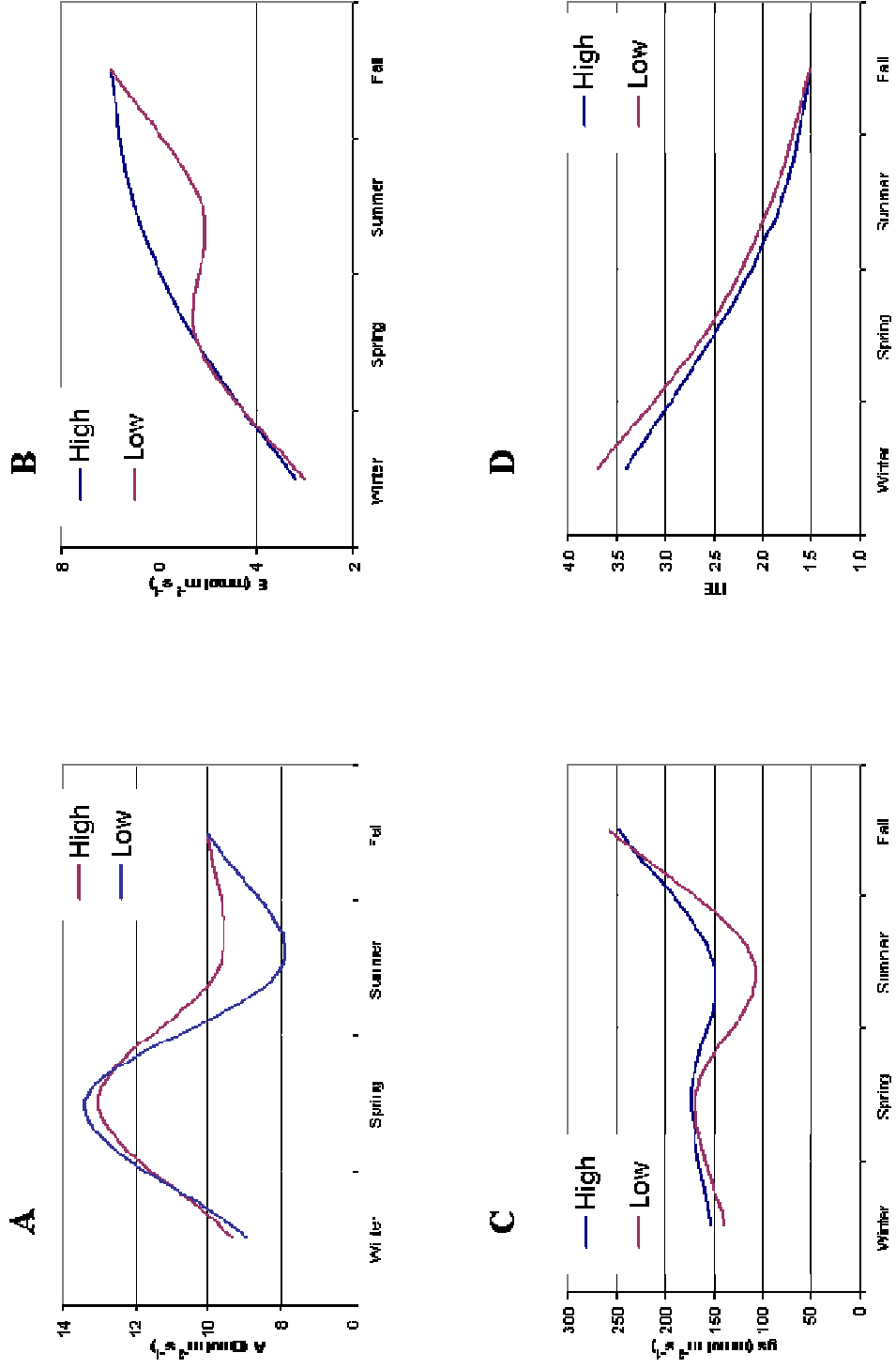
Figure 4.6. Seasonal patterns of mean CO_2 assimilation (A), transpiration (E), stomatal conductance (gs) and instantaneous transpiration efficiency (ITE) in response to high or low irrigation rate from mixed taxa in experimental plots.
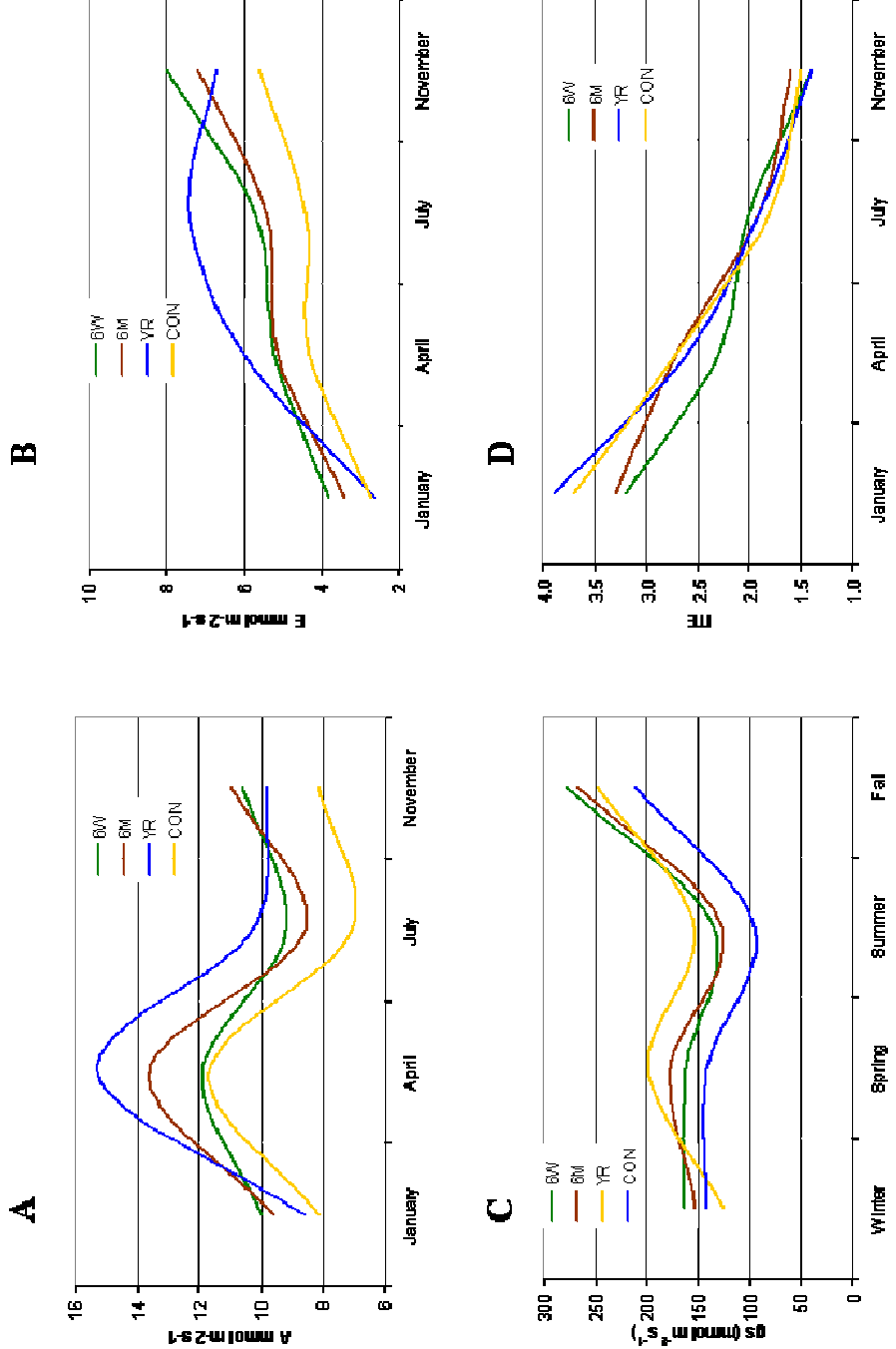
Figure 4.7. Seasonal patterns of mean CO$_2$ assimilation (A), transpiration (E), stomatal conductance (gs) and instantaneous transpiration efficiency (ITE) in response to shrub pruning regimes (hedged every 6 weeks or 6 months, renewal pruned yearly, or unpruned) for pooled measurements of trees, shrubs and ground covers in experimental plots.

treatments. Highest ITE occurred in all treatments during the winter and lowest during the fall.

Plant taxa within plots differed considerably in their mean gas exchange fluxes over 2 years (figure 4.8). E*ucalyptus* had the highest fluxes of A per unit leaf area, averaging 14.2 umol m^{-2} s^{-1}. *Quercus* and *Nerium* had similar rates of A, somewhat higher than those for *Rosmarinus* and *Leucophyllum*.   Plant taxa also differed in fluxes of E and gs, ranging from high values of 6.9 and 230 mmol m^{-2} s^{-1} for *Quercus* and lows of 4.7 and 154 mmol m^{-2} s^{-1} in *Leucophyllum,* for E and gs, respectively. *Eucalyptus* and *Nerium* had highest overall ITE (2.9 and 2.7, respectively) with other taxa ranging from 1.7-2.0.

Plot CAP and TP

Strategies for scaling and integration of gas exchange data were based on species and treatment effect patterns on PP, LA, and instantaneous gas exchange fluxes. Integrated data are presented by treatment main effects only because neither whole plot PP nor gas exchange fluxes were affected by treatment interaction.

Trapezoidal integration of A predicted total landscape CAP of 289.0 and 216.8 kg in high and low irrigation application rates, respectively, while predicted TC for those treatments was 95.9 and 53.0 kg (Table 4.4), representing 33 and 24% of total CAP. Despite lower instantaneous leaf level fluxes of A in unpruned control plots, high mean LA in that treatment resulted in the highest predicted maximum CAP for the 3 year study period, while estimated TC was the lowest in those plots at 17% of CAP. Regression of TC on CAP for the 14 plots indicated that overall TC was 34% of that estimated by the maximum CAP model (P-value 0.002, figure 4.9).

81
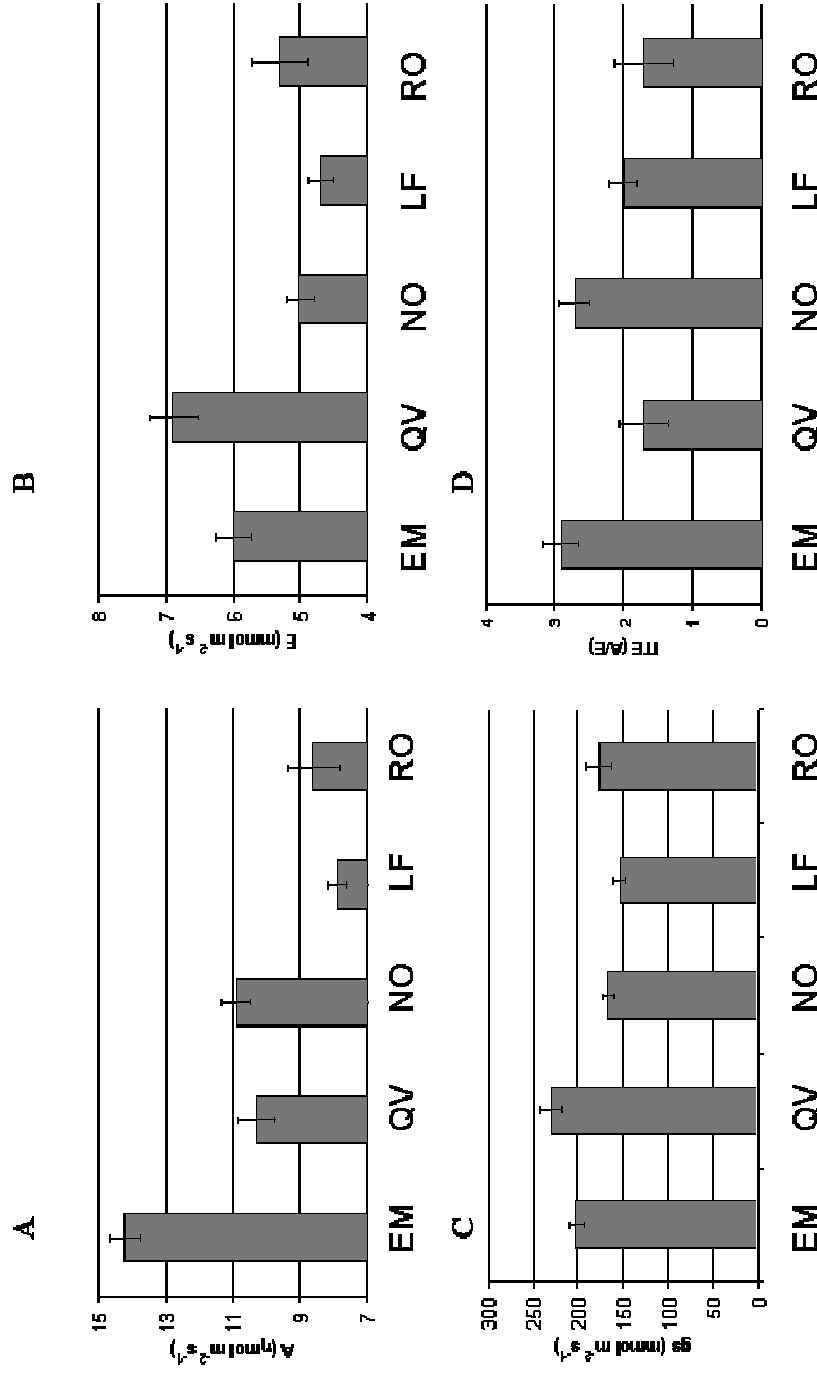
Figure 4.8. Mean fluxes of CO$_2$ assimilation (A), transpiration (E), stomatal conductance (gs) and instantaneous transpiration efficiency (ITE) in *Eucalyptus microtheca* (EM), *Quercus virginiana* (QV) *Nerium oleander* (NO), *Leucophyllum frutescens* (LF), and *Rosmarinus officinalis* (RO) over 2 years.
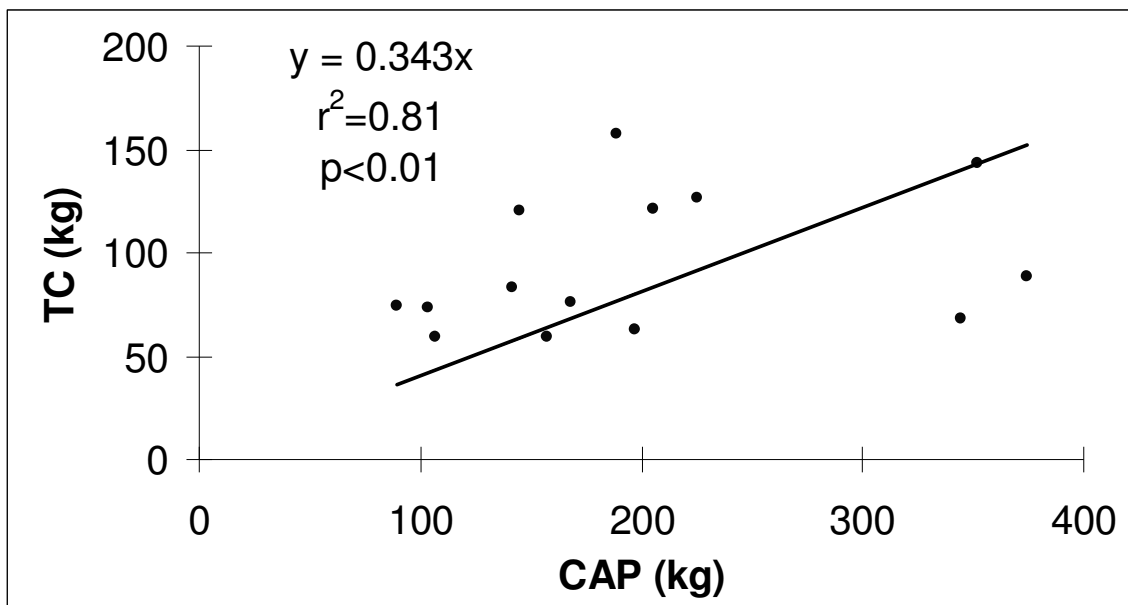
Figure 4.9. Regression analysis of estimated total landscape carbon uptake (TC in kg) on

predicted maximum carbon acquisition potential (CAP in kg) for 14 experimental plots.

Table 4.4. Estimated total plot carbon uptake (TC) in kg, predicted landscape maximum carbon acquisition potential via trapezoidal integration (CAP), predicted total landscape maximum water loss potential (TP), irrigation application efficiency (IAE) as a fraction of total water applied via irrigation), and the ratio of irrigation application (IA) to mean canopy leaf area (LA) as a function of high or low irrigation rate or pruning regime (shrubs hedged every 6 weeks or every 6 months, yearly renewal pruned, or unpruned controls) for three years in simulated landscape plots.

	TC (kg)	CAP (kg)	TC: CAP	TP (Lx10^3)	IAE	IA: LA
Irrigation						
High rate	95.9	289.0	0.33	121.2	0.62	0.40
Low rate	53.0	216.8	0.24	76.7	0.94	0.25
Shrub pruning						
6 week hedge	72.1	181.4	0.40	85.2	0.62	0.49
6 month hedge	82.3	274.7	0.30	114.2	0.83	0.28
Yearly renewal	80.8	196.4	0.41	78.3	0.57	0.41
Unpruned	62.7	359.1	0.17	118.2	0.86	0.22

Trapezoidal integration of E predicted total landscape TP of 12.1 x 10^4 and 6.17x 10^4 L for the three year study in high and low irrigation treatment plots, respectively (Table 4.4). Plots given high irrigation rate had irrigation application efficiency (IAE, fraction of irrigation applied potentially transpired) of 0.62 and those given low rate had an IAE of 0.94. Pruning effects on landscape maximum TP reflected total mean plot LA more than leaf level processes, and plots with shrubs left unpruned had the highest estimated TP of 1.8 x 10^5 over the three year study period.   Plants in plots pruned yearly had the lowest overall TP at 7.8 x 10^4 L for three years, and the lowest IAE at 0.57 (Table 4.4).

Mass sap flow in Nerium

Representative trends in mean daily mass sap flow per unit leaf area and scaled to the whole plant for *Nerium* in each irrigation and pruning interaction combination are shown in figures 4.10 and 4.11.   In general, the plants with the lowest LA, those pruned every 6 weeks, had the highest mass sap flow fluxes per unit leaf area from May through July, with mean values of 1.35 and 2.76 L m^{-2} day^{-1} of water loss in high and low irrigation rate treatments, respectively.   Scaled to the whole plant, those with the most LA at the time of measurement (plants pruned every 6 months and given high irrigation rate) had the highest rate of average daily total water loss at 13.3 L per day.   Plants renewal pruned in February did not have adequate stem diameter to use the stem flow gauges until October when VPD was lower and irrigation had been ramped down, and flow patterns reflect those changes.
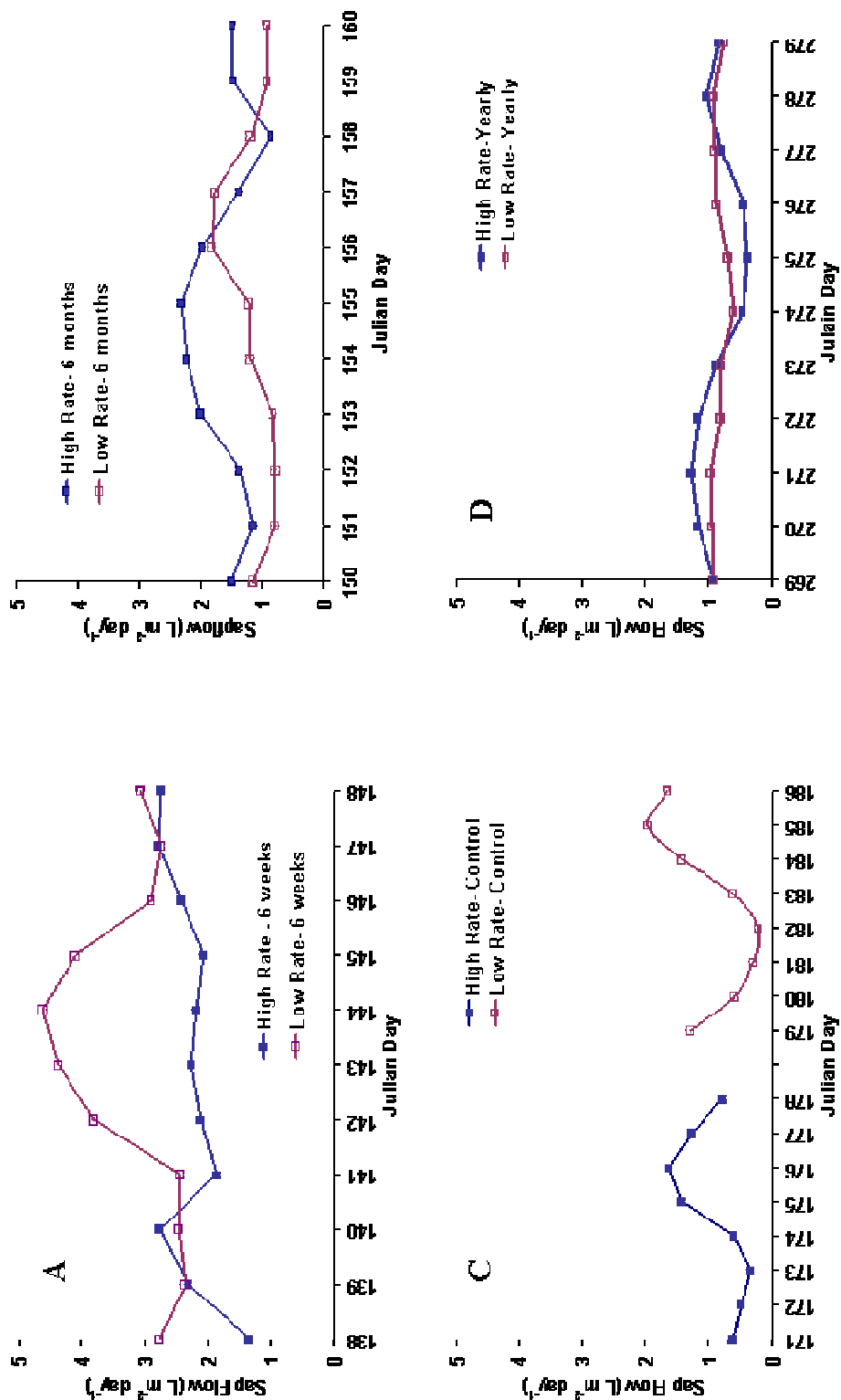
Figure 4.10. Patterns of mass sap flow in L m^{-2} of leaf area for *Nerium oleander* during 2002 under high and low irrigation rate treatments for plants (A) pruned every 6 weeks, Julian Days (JD) 138-148 (B) pruned every six months, JD 150-160 (C) unpruned controls, JD 171-186 or (D) pruned yearly, JD 269-279. Values are daily means for 4 replicates of each
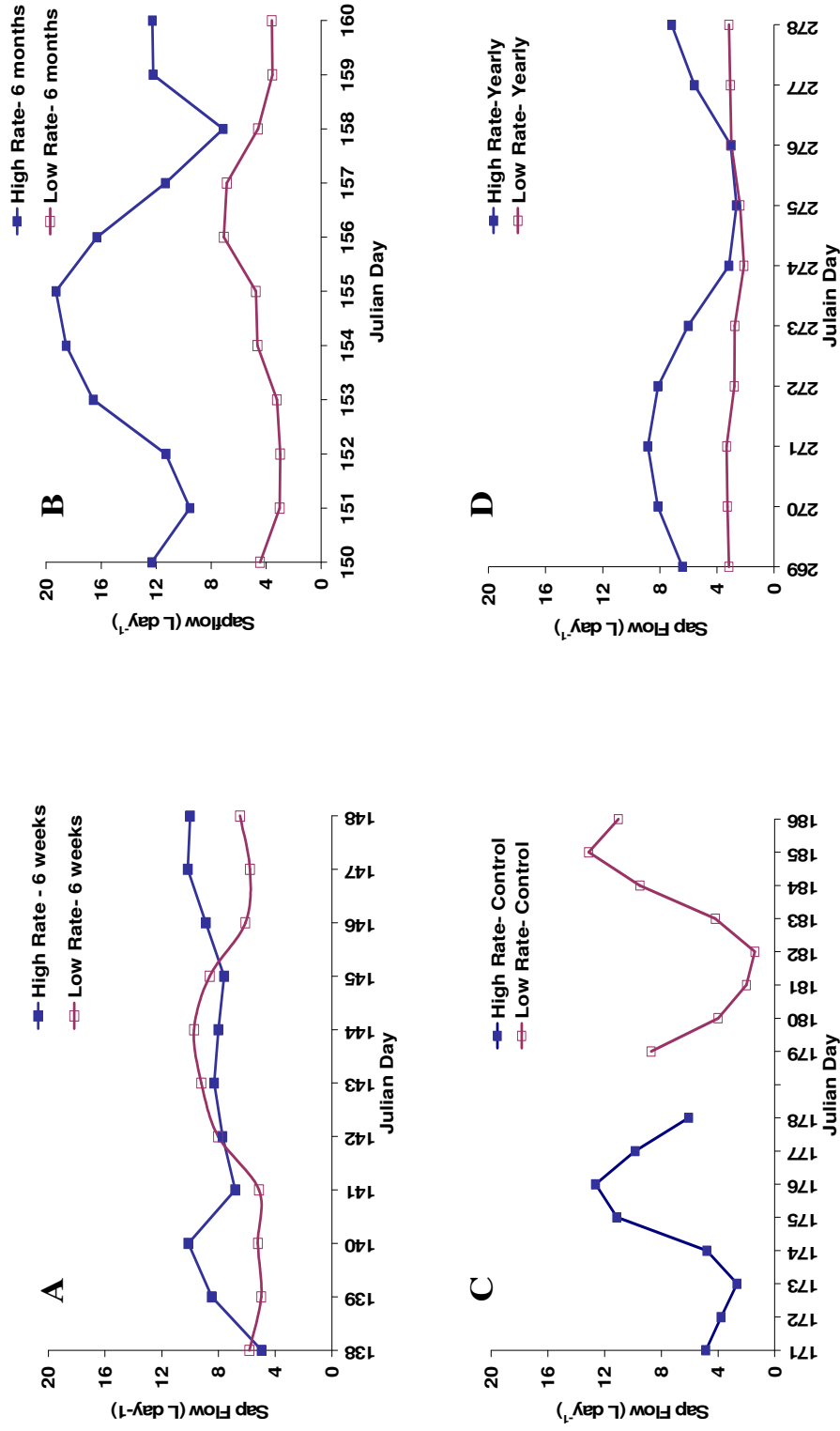
Figure 4.11. Patterns of whole plant mass sap flow in *Nerium oleander* during 2002 under high and low irrigation rate treatments for plants (a) pruned every 6 weeks, Julian Days (JD) 138-148 (b) pruned every six months, JD 150-160 (c) unpruned controls, JD 171-186 or (D) pruned yearly, JD 269-279. Values are daily means for 4

Estimated daily whole plant E in *Nerium* calculated via scaling of mass sap flow data and trapezoidal integration of gas exchange data and total irrigation application volume

 (IA) for the measurement period are shown for data collected between Julian Days 138-186 in figure 4.11. For all treatment combinations except the 6 week pruning, maximum TP was greater than IA. Under low rate irrigation, estimates of daily water loss via sap flow ranged from 27% to 87% of predicted maximum TP in unpruned controls and plants hedged every six weeks, respectively.   Under high irrigation rate, estimated daily sap flow ranged from 31-51% of the predicted maximum. Regression of mass sap flow on predicted maximum TP showed no significant relationship (data not shown).

Discussion

These data suggest that irrigation and pruning alter whole plot PP and WUE$_I$ via effects on both average plot LA and on instantaneous leaf level processes.   High irrigation rate increased PP and LA, but not mean maximum instantaneous fluxes of A on a leaf area basis, suggesting that irrigation most influenced maximum plot CAP and PP via effects on LA. Pruning treatment effects on shrub PP did not affect whole plot PP, but did influence total plot LA which ultimately translated to differences in whole plot CAP. However, observed patterns of PP and TC in the irrigation and shrub pruning treatment combinations were not consistent with predictions of maximum plot CAP, suggesting interactive effects of leaf level and whole plant processes on PP not captured by the CAP model.
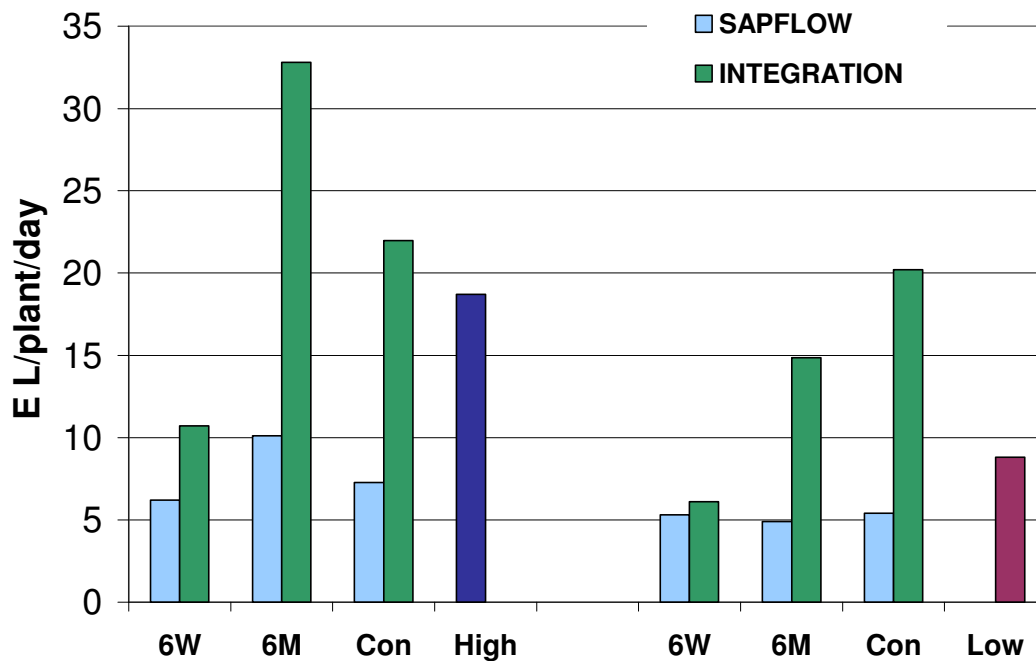
Figure 4.12. Mean daily whole plant water loss in *Nerium oleander* as calculated via mass sap flow measurements and predicted maximum whole plant water loss potential via the trapezoidal integration model as a function of irrigation and pruning treatment combinations and mean daily irrigation application volume for high and low rate irrigation treatments.

Whole plot water relations also reflected interaction of LA and leaf level processes. High irrigation rate increased LA by 50% and instantaneous E by 8%, and values for each taxa scaled to the whole plot translated to a 57% increase in maximum TP. High irrigation rate decreased ITE by only 4%, while whole plot WUE_I was decreased by 23%. Much of the difference in these parameters might be explained by evaporation of water applied directly from the soil. As with PP, pruning effects on shrub WUE_I did not scale to whole plot effects. Pruning effects of leaf level fluxes of E were not consistent with predicted patterns of maximum TP, which was most influenced by treatment effects on LA.

The CAP and TP model assumes that all leaves on a plant have equal conductance, irradiance, and photosynthetic capacity, an assumption likely more valid for some pruning treatments than for others. Plots with shrubs left unpruned or pruned every 6 months had highest LA had the lowest TC: CAP ratios, which might indicate some self shading or reduced gs within denser canopies. Predictions of plot CAP and TP might be overestimated for landscapes with denser canopies. In addition, the gas exchange sampling strategy used in this experiment failed to incorporate possible treatment differences in plant gas exchange fluxes during periods of reduced soil moisture availability within the irrigation cycle.

Patterns of CAP, TP, and mass sap flow in *Nerium* suggest that water availability per unit of canopy leaf area (IA:LA) might influence leaf level processes and ultimately have the greatest impact on landscape level carbon and water dynamics. Patterns of the ratio of whole plot TC to CAP were similar to those of IA:LA for both irrigation and pruning treatments. While high rate irrigation decreased IAE, pruning effects on that parameter

were solely influenced by LA, with increased LA leading to increased IAE, suggesting

that much of the water applied via irrigation was lost via evaporation in plots where

lower LA decreased plant TP.   Although no estimates of whole plot transpiration were

made, mass sap flow measurements in *Nerium* suggest that for that species, whole plant

water loss was limited by irrigation application rate. Under high irrigation application

rate, daily whole plant water loss measured via sap flow in *Nerium* ranged from 33-54%

of irrigation application volume and increased with LA, with little difference per unit leaf

area.   Under low irrigation application rate, daily whole plant water loss was similar in

all pruning treatments independent of LA, with values ranging from 55-61% of water

applied, while varying per unit leaf area. One possible explanation for these responses

might be that gs was reduced prior to irrigation events and variation in leaf level gas

exchange was not detected via measures of maximum gas exchange fluxes under well

watered conditions.

   During the three years of this study, plants in plots designed to resemble local SFR

landscapes received mean annual irrigation of 814 and 1954 L m^{-2} y^{-1}, under low and high

irrigation application rate treatments, respectively.   Martin and Stabler (2002) reported

that residential homeowners in the Phoenix metropolitan area applied on average 1114 L

m^{-2} to mature and fully established xeric-style landscape plantings (no turf present), but

those data showed considerable variance, with irrigation rate ranging from 788 to 2243 L

m^{-2}

y^{-1}. Mean instantaneous fluxes of A for a variety of taxa were similar in this controlled

experiment to those measured by Martin and Stabler *in situ* in urban landscapes (mean A

10.9 µmol m^{-2} s^{-1}), while mean instantaneous fluxes of E were somewhat lower in the

current study (5.4 mmol m^{-2} s^{-1} in the current study vs. 7.4 mmol m^{-2} s^{-1}) despite

somewhat similar irrigation application rates. These differences might reflect variation in

plant taxa, differences in IA:LA (no data available from Martin and Stabler), or

differences in the relative contribution of precipitation to plant water availability (213

mm y^{-1} during the 1998-99 Martin and Stabler study vs. 114 mm y^{-1} during the current

study).

Although PP of landscapes given lower irrigation rates was reduced, those plots

generally had higher WUE$_I$ and IAE. While shrub pruning did not affect landscape PP or

WUE$_I$, IAE was reduced by pruning in plots with lower mean LA, suggesting that

irrigation application rate might be modified to maximize WUE$_I$ and IAE based on LA.

Pruning regimes are also clearly significant in terms of understanding plant carbon

and water dynamics in urban landscapes.   All pruning treatments for shrubs in this study

increased leaf level fluxes of A and E relative to plots in which shrubs were not pruned,

but those practices did not translate directly to decreases in plot PP or TP because of

standing LA dynamics. While pruning of shrubs affected PP for pruned taxa, that

practice had no effect on whole plot PP but a marked affect on LA, CAP, and TP.

Pruning also dramatically affected GW production and landscape carbon storage such

that plots with shrubs renewal pruned ultimately stored only about 20% of PP.   The

effects of various irrigation and pruning regimes on the carbon and water cycling of

landscape processes in this study demonstrate the need to understand how heterogeneous

management influences urban plant ecology and to incorporate such factors in efforts to

understand urban ecosystem processes to promote sustainable urban environments.

CHAPTER 5: IMPLICATIONS FOR LANDSCAPE MANAGMENT

Urban plant distribution

The distribution of plants in urban ecosystems reflects myriad influences at multiple scales. At the broadest spatial and temporal scales, vegetation density and resultant plant ecosystem function are influenced by policy makers and urban planners via decisions about urban development, socioeconomic land use, and various land management decisions intended to conserve natural resources or preserve open space. This is the scale at which urban foresters can best contribute to sustainable landscape management via knowledge of plant effects on ecosystem processes and recommendations for appropriate plant distribution within various land uses to address issues such as urban heating and resource conservation.

Data presented in Chapters 2 and 3 indicate that socioeconomic land use influences land cover, plant canopy, and microclimate in the CAP-LTER study area. While the descriptive data presented in Chapter 2 offer some characterization of plant canopy cover in various land uses, those data are most useful for SFR land uses because of the limited number of sites sampled within the other urban land use categories. NDVI as a descriptor of actual vegetation distribution and leaf area density in urban areas has very limited applications; Paine (2002) found no significant relationship between NDVI and 2 or 3 dimensional plant canopy based on field data collected for the CAP-LTER 200 site survey. Significant correlations between NDVI and various microclimate parameters were presented in Chapter 3, but consistent statistical relationships that might predict microclimate based on NDVI were confounded by other influences such as cover by anthropogenic surfaces and distance from the urban core. Use of NDVI in urban climate

planning is probably most useful in terms of understanding how urban sprawl and broad spatial and temporal scale land conversions from desert or agricultural land uses to urban uses influence local climate, rather than for land use or management decisions within the urbanized area.

The most predominant land use in the CAP-LTER study area, SFR, although relatively well represented by data presented in Chapter 2, is probably least influenced by top down management decisions and most likely to represent heterogeneous vegetation distribution and maintenance practices. This is the scale at which landscape horticulturalists and architects, using data from ecophysiological studies such as that put forth in Chapter 4, can contribute via analysis of performance characteristics of various taxa and plant ecosystem function under a variety of maintenance regimes. Current trends in urban development and landscape management include creation of planned communities with legally binding covenants, codes, and restrictions (CCR) that can influence plant distribution and species composition (Martin, et al., 2002), and exert some level of top down control of SFR landscape characteristics. Newer planned communities in some states even incorporate centralized irrigation controls (Tom Yeager, University of Florida Extension, personal communication). In addition, government agencies such as the Arizona Department of Water Resources (ADWR) increasingly influence zoning laws and management decisions in terms of vegetation density and plant taxa used in public and private landscapes and can make wise management decisions based on sound horticultural research data. Data presented in Chapter 4 suggest that relative canopy cover by various plant taxa might significantly impact landscape plant carbon and water cycling because of taxonomic differences in leaf level fluxes of A and E.

Within the urbanized area, ground based data from studies such as the 200 site survey might be used in conjunction with estimates of whole plot level processes to make predictions about plant ecosystem function in an urbanized area (Zipperer, et al., 1997). Data from Chapter 2 indicate that within the CAP-LTER study area mean above ground plant canopy area in 53.3% of urban landscapes (SFR plots) was approximately 119-145 m^2 per 900 m^2 of land, or 13-16% of the two dimensional land area. Landscape LAI of the experiemental plots described in Chapter 4 ranged from 1.4 to 3.1 over time under very disparate irrigation and pruning regimes, while average values of LAI over the 3 year study period were slightly more conservative, ranging from 1.6 to 2.7. These data suggest that total LA within SFR land use might be expected to range on average between 18.2 and 43.2 m^2 per 100 m^2 of land area under all maintenance regimes, with a mean value of 29.9 m^2 per 100 m^2. Knowledge of the effects of landscape maintenance practices such as irrigation and pruning might improve predictions about l landscape LA considerably. More data are needed to elucidate how land use influences total plant canopy area in non SFR land uses.

Irrigation and pruning of urban plants

Conservation of fresh water resources has become a primary concern for urban planners and within the green industries at the same time that urban development has led to increased irrigation of amenity landscape plants. Efficient use of water resources for urban greening must be weighed appropriately in terms of the benefits that plants provide in cities, and management strategies should aim to maximize landscape irrigation efficiency. Frequent pruning of shrubs to control size and maintain a neat landscape

appearance is increasingly common in the CAP-LTER study area, and is even mandated

by city ordinances and neighborhood CCR. Data from the previous chapter suggest that

pruning, as well as irrigation rate, might influence the efficiency of landscape irrigation

and plant water use.

Data presented in Chapter 3 indicated that within the CAP-LTER urban ecosystem,

vegetation in agricultural and urban areas affected local microclimates, and that there was

some association between vegetation density and air temperature over space and time.

Existing models of urban microclimates are based on the energy balance equation:

$$Q_{net} = Q_H + Q_E + Q_S$$

where Q_{net} is net radiation, Q_H is sensible heat flux, Q_E is the latent heat flux associated

with evapotranspiration, and Q_S is stored heat (Oke, 1988). Research has shown that

Q_{net} is similar across urban areas and can generally be assumed to have been equal across

transects for all land uses (Oke, 1988) in the study described in Chapter 3. Therefore,

measured differences in Q_H (air temperature) must have been function of differences in

Q_E and Q_S that existed as a function of land cover characteristics and water availability.

In any given landscape, increased volume of water associated with irrigation and

available for Q_E should always decrease Q_H to some degree, and the magnitude of that

affect should be influenced by the total surface area available for energy exchanges.

Irrigation application rate influenced total LA, instantaneous fluxes of E per unit leaf

area, and maximum plant TP in experimental plots, suggesting several mechanisms for

irrigation related plant influences on air temperature. Average total plot LA was

increased by 50% under high rate irrigation regimes, suggesting that total latent heat flux

might be similarly increased under well watered conditions, assuming similar leaf

conductance to water vapor within the landscape canopy. Irrigation effects on instantaneous leaf level fluxes of E might also influence the relative balance of Q_E and Q_H. During summer months, the season in which greatest disparity in urban temperatures were detected along transects in Phoenix, instantaneous leaf level fluxes of E were increased by 27% in experimental plots receiving high rate irrigation, suggesting that vegetation in landscapes with similar standing LA might vary in total latent heat flux and influence temperature variably as a function of irrigation rate. Such influences on air temperature might not be detected via measures of vegetation density such as NDVI. Irrigation most likely influences plant effects on microclimate via interaction of LA and instantaneous fluxes of E and subsequent effects on maximum landscape plant TP. In Chapter 4, a 58% decrease in irrigation application rate decreased maximum plant TP by only 36%, however, we might assume that irrigation water applied but not transpired by the plant is still subject to latent heat flux and therefore has an influence on energy balance independent of plant transpiration.

Within the CAP-LTER urban ecosystem, irrigation is a primary determinant of CO_2 uptake and productivity by landscape plants. Martin and Stabler (2002) estimated that mean CAP was 1.19 kg C $m^2 yr^{-1}$ of leaf area for irrigated residential landscapes in the Phoenix metropolitan area, similar to estimates of 1.20 kg C $m^2 yr^{-1}$ leaf area obtained in the experimental plots in Chapter 4. While irrigation application rate did not affect instantaneous leaf level fluxes of A overall, the increase in LA associated with the high irrigation rate could scale to approximately 36 kg of additional carbon uptake per 100 m^2 of landscape area per year in the typical SFR plot (based on mean LA 29.9 m^2 per 100 m^2 of land area in experimental plots) described in Chapter 2. Based on these figures, high

irrigation application rates similar to those monitored by Martin and Stabler (2002) in the estimated 1168 km^2 of residential land use in the CAP-LTER ecosystem (Stefanov et al., 2001) might increase total C uptake in the CAP-LTER ecosystem by 360,000 kg per year relative to lower irrigation application rates.

Various shrub pruning regimes affected also average landscape LA, and those effects might influence urban microclimates and CAP and TP by varying degrees via scaling calculations similar to those described above. In addition, while pruning did not affect whole plot PP, plant biomass removed via pruning represents carbon taken out of the plant storage pool and potential loss of nutrients returned to the soil as litter, as well as creating green waste that must be disposed of in land fills or via mulching programs. It is assumed that over 94% of the carbon associated with biomass is permanently stored via anaerobic conditions when green waste is disposed of in landfills, however mulched green waste is probably all remineralized to CO_2 within 3 years as would be litter in natural ecosystems (Micales and Skog, 1997; Scheu and Schauermann, 1994). Current trends in green waste management favor mulching due to limited space in landfills (EPA, 2003). The fraction of total landscape above ground PP removed via pruning ranged from 7.5% in plots with no shrub pruning to 79.4% in plots with shrubs renewal pruned yearly.

Data presented here suggest that irrigation and pruning can influence urban plant ecosystem function in terms of potential effects on microclimate and landscape carbon and water cycling.   More data are needed to elucidate current trends is landscape irrigation and pruning practices by municipalities, commercial contractors and private

citizens in order to improve quantitative predictions of plant ecosystem function in urban landscapes.

WUE of urban amenity landscapes

Data from Chapter 4 that address irrigation and pruning effects on plant water use and transpiration efficiencies as traditionally defined by agronomists and ecologists have little relevance in terms efficient use of water for amenity landscape plants. Terms such as water use efficiency and irrigation application efficiency have been given a variety of definitions in the literature (Eamus, 1991), but in general all describe the some relationship between plant productivity (biomass or carbon assimilation) and the amount of water applied to or transpired by plants.

Urban amenity landscapes are installed and maintained to fulfill social and ecological functions. In contrast to agro ecosystems where maximum plant productivity is a desired outcome, space and maintenance requirements in urban areas make size control via optimization of plant growth a more practical consideration for landscape managers, so biomass production as a measure of landscape water use efficiency might not be appropriate. While uptake of atmospheric CO_2 and associated improvement in air quality might be considered a benefit associated with urban plants and an appropriate measure of urban plant water use efficiency (UWUE), much of that benefit might be nullified by subsequent pruning regimes and green waste management.

Optimum UWUE might also change over time. Rapid growth and establishment might be desired in newly installed landscapes, while size control might be more

important as they mature. Stabler and Martin (2000) found that WUE and ITE in response to irrigation frequency varied over time for two woody plant species.

Irrigation practices further complicate the concept of UWUE. Applying various traditional definitions for irrigation and water use efficiency to data from Chapter 4 can produce conflicting results and conclusions.   Defining UWUE in terms of irrigation application rate as either PP or CAP per unit of water applied elicits maximum efficiency under low irrigation rate for both ratios, but pruning treatment effects differ (Table 5.1). Plots with shrubs left unpruned have the lowest value for the ratio of PP/IA and the highest for the ratio CAP/IA.   In contrast, if UWUE is defined in terms of PP or CAP per maximum TP, alternative irrigation and pruning treatments elicit maximum efficiency. For the ratio PP:TP, maximum efficiency occurred under high rate irrigation or with shrubs pruned yearly, while the ratio of CAP:TP elicited maximum efficiency under low rate or in plots with shrubs left unpruned.

In Phoenix, where virtually all landscape plantings have supplemental water added via irrigation, irrigation application rate might be a more appropriate measure of UWUE than actual plant transpiration or TP, while the latter measures might be more appropriate in less arid cities where plants are less dependent on supplemental irrigation. In data presented in Chapter 4, maximum landscape TP clearly overestimated actual plant transpiration in *Nerium*, likely due to stomatal limitation of water loss prior to irrigation events or reductions in gs due to canopy density, data not captured via the sampling protocol or model used. Measures of maximum and minimum gas exchanges fluxes under conditions of varying soil moisture and other scaling strategies might elicit better predictions of actual landscape TP.   Data from Chapter 4 showed that human regulated

inputs of water have more impact on efficiency of irrigation than do plant physiological processes, suggesting that irrigation application rate might be a primary determinant of UWUE in the CAP-LTER ecosystem. Differences in WUE_I and ITE of various plant taxa suggest that species selection might be more important in other cities where actual landscape TP is most important.

Although management of urban plants currently emphasizes their socioeconomic functions, incorporation of those functions into definitions for UWUE is difficult to quantify. Current trends in environmental horticulture and urban landscape management stress establishment of aesthetic thresholds and tolerance levels for pests and pathogens in amenity plants, and might also be applied to irrigation needs. Informal surveys conducted at the experimental plots described in Chapter 4 indicated that while irrigation rate did not affect overall plant aesthetic rating, the plots with the lowest irrigation to LA ratio (unpruned controls) had the lowest aesthetic rating (data not shown). Other practical considerations, such as maintenance time and green waste production might be incorporated into a practical definition of UWUE. At the experimental plots, maintenance time increased with shrub pruning frequency, and total green waste production was affected markedly by pruning.

Sound landscape management practices to promote sustainable urban environments can be developed via understanding of urban ecosystem processes at multiple scales. Urban foresters and landscape architects can contribute to long term, broad spatial scale planning processes via knowledge of vegetation and land cover effects on ecosystem processes, such as microclimate modification. Landscape horticulturalists can contribute via evaluation of plant performance, species characteristics, and ecophysiological

responses to various maintenance regimes. More data are needed to evaluate plant

performance thresholds and to incorporate non-traditional considerations into definitions

for UWUE.

Table 5.1. Alternative measures and values of urban plant water use efficiency, expressed as ratios of above ground productivity (PP, kg) or maximum carbon acquisition potential (CAP, kg) to irrigation application volume (IA, 10^3 L) or maximum transpiration potential (TP 10^3 L) in experimental plots in response to irrigation rate and pruning regime treatments for three years.

Ratio:	PP/IA	CAP/IA	PP/TP	CAP/TP
Treatment				
Irrigation Rate				
High	0.59	1.72	0.81	2.38
Low	0.76	3.14	0.68	2.83
Shrub Pruning				
6-week	0.61	1.54	0.84	2.12
6-month	0.69	2.33	0.72	2.40
Yearly	0.68	1.66	1.02	2.51
Control	0.53	3.04	0.53	3.04

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APPENDIX A

REGRESSION ANALYSES TO PREDICT LEAF AREA IN CM^2 BASED ON LEAF

DRY WEIGHT IN MG FOR *NERIUM* AND *LEUCOPHYLLUM*.

Regression Plot
Split By: Species
Cell: oleander

$Y = 0 + .045 * X; R^2 = .983$

Regression Plot
Split By: Species
Cell: sage

$Y = 0 + .092 * X; R^2 = .991$
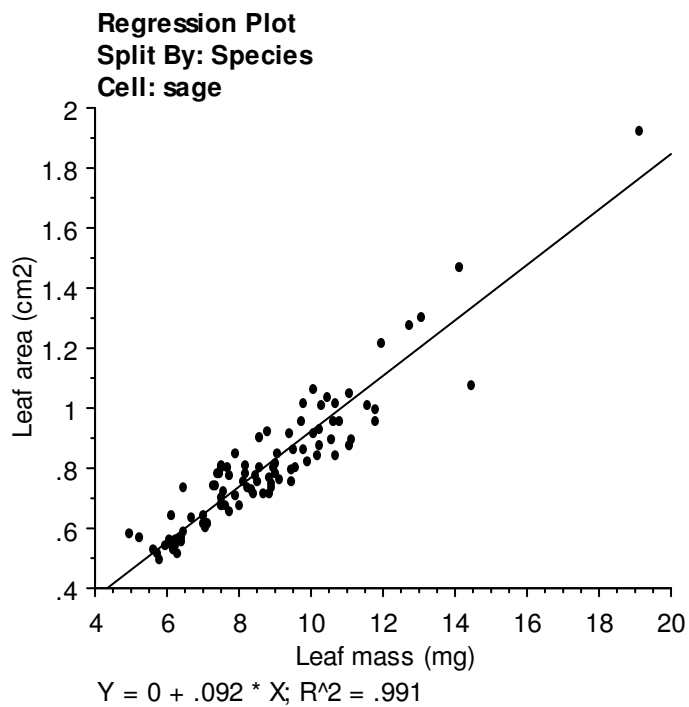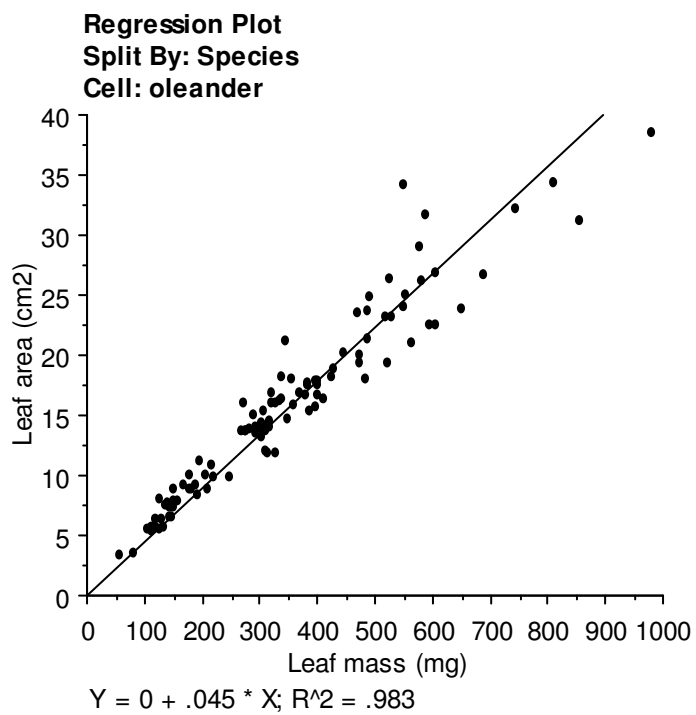
APPENDIX B

REGRESSION ANALYSES TO PREDICT CANOPY LEAF AREA IN M^2 BASED ON

SHRUB CANOPY VOLUME IN M^3 FOR *NERIUM* AND *LEUCOPHYLLUM*

ANOVA for all regression coefficients are significant (P<0.001).

Regression Plot
Split By: species, irrigation, prune
Cell: Leucophyllum, High Rate, 6 month

Y = 0 + 2.419 * X; R^2 = .942

Regression Plot
Split By: species, irrigation, prune
Cell: Leucophyllum, High Rate, 6 week

Y = 0 + 1.903 * X; R^2 = .986

Regression Plot
Split By: species, irrigation, prune
Cell: Leucophyllum, High Rate, control

Y = 0 + .51 * X; R^2 = .948

Regression Plot
Split By: species, irrigation, prune
Cell: Leucophyllum, High Rate, yearly

Y = 0 + .561 * X; R^2 = .99

Regression Plot
Split By: species, irrigation, prune
Cell: Leucophyllum, Low Rate, 6 month

$Y = 0 + 2.071 * X; R^2 = .83$

Regression Plot
Split By: species, irrigation, prune
Cell: Leucophyllum, Low Rate, 6 week

$Y = 0 + 2.745 * X; R^2 = .958$

Regression Plot
Split By: species, irrigation, prune
Cell: Leucophyllum, Low Rate, control

Y = 0 + .646 * X; R^2 = .974

Regression Plot
Split By: species, irrigation, prune
Cell: Leucophyllum, Low Rate, yearly

Y = 0 + .587 * X; R^2 = .989

Regression Plot
Split By: species, irrigation, prune
Cell: Nerium, High Rate, 6 month

Y = 0 + 3.223 * X; R^2 = .983

Regression Plot
Split By: species, irrigation, prune
Cell: Nerium, High Rate, 6 week

Y = 0 + 1.904 * X; R^2 = .992

Regression Plot
Split By: species, irrigation, prune
Cell: Nerium, High Rate, control

Y = 0 + .563 * X; R^2 = .99

Regression Plot
Split By: species, irrigation, prune
Cell: Nerium, High Rate, yearly

Y = 0 + .854 * X; R^2 = .973

Regression Plot
Split By: species, irrigation, prune
Cell: Nerium, Low Rate, 6 month

$Y = 0 + 2.969 * X; R^2 = .972$

Regression Plot
Split By: species, irrigation, prune
Cell: Nerium, Low Rate, 6 week

$Y = 0 + 2.29 * X; R^2 = .994$

Regression Plot
Split By: species, irrigation, prune
Cell: Nerium, Low Rate, control

Y = 0 + .738 * X; R^2 = .972

Regression Plot
Split By: species, irrigation, prune
Cell: Nerium, Low Rate, yearly

Y = 0 + 1.09 * X; R^2 = .983