

EVALUATING IMPACTS OF DROUGHT AND CONSERVATION MEASURES  
ON URBAN VEGETATION IN SOUTHERN CALIFORNIA

by  
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## ABSTRACT

Water resource managers in southern California are relying on a range of conservation measures, from changes in pricing structure to mandatory restrictions, to influence demand and ensure resiliency of water supply in the face of ongoing drought and long-term climate change. Improved quantification of these measures is critical for evaluating efficacy and consumer response. The current study investigates the impact of recent drought and conservation measures on vegetation greenness and water consumption in urban areas across southern California. Previous research has shown that vegetation greenness in urban areas is associated with outdoor water consumption. Evaluating these parameters provides useful insight on how water demand responds to changes in water policy and natural events, such as drought. Data are compared across several water districts in Los Angeles, Orange County, and San Diego to identify how response varies with different conservation efforts in regions sharing similar climatology. The comparison expands on previous work conducted in Los Angeles evaluating outdoor water consumption patterns in single family residential areas. Remotely-sensed vegetation (MOD13/MYD13) products from MODIS are evaluated (8-day time step and 250-meter spatial resolution) over approximately 14 years to identify trends related to drought and conservation events. Furthermore, study parameters are examined over various land use types and compared across water districts to explore differences in outdoor water use and corresponding drivers. Trends are compared to water consumption to gain a better understanding of how recent conservation measures have influenced water demand. Ultimately, results will contribute to improved understanding of the response of water demand to drought and conservation measures and will aid in the implementation of effective conservation strategies across the southern California region.

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## LIST OF ABBREVIATIONS

AFY	acre-feet per year
EVI	enhanced vegetation index
FY	Fiscal Year
GPCD	gallons per capita day
HB	City of Huntington Beach
IRWD	Irvine Ranch Water District
LA	City of Los Angeles
LADWP	Los Angeles Department of Water and Power
LVMWD	Las Virgenes Municipal Water District
MFR	multi-family residential
MODIS	Moderate Resolution Imaging Spectroradiometer
MWD	Mesa Water District
NASA	National Aeronautics and Space Administration
NCDC	National Climatic Data Center
NDVI	normalized difference vegetation index
PDSI	Palmer Drought Severity Index
PRISM	Parameter-elevation Regressions on Independent Slopes Model
RMSE	root mean square error
SANDAG	San Diego Association of Governments
SCAG	Southern California Association of Governments
SD	City of San Diego
SFR	single-family residential
WY	Water Year

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## CHAPTER 1 INTRODUCTION

In the southwestern United States, climate change is expected to bring increasing temperatures, higher probability of severe drought, and reduction in surface water flow (EPA 2012). These effects may present significant challenges related to water resources in the semi-arid west. Since 2012, California has been in the midst of the most severe drought on record and faces several water-related issues such as water supply shortage, groundwater overdraft, and streamflow reduction (Diffenbaugh et al. 2015). However, a study by Gleick et al. (2003) suggests that California's urban water needs can be met by revised water policies, conservation efforts, and high-efficiency technology. Because of the prospect of meeting California's water demand through conservation and improvements in efficiency, there is an increasingly important need for accurate quantification of the effects of water conservation and drought.

Although agriculture accounts for over three-quarters of California's total water use, there is still significant potential for conservation in the urban water use sectors (Gleick et al. 2003). Conservation and efficiency improvements in the urban sector have the potential to save California a total of 2.9 million to 5.2 million acre-feet per year, compared to the average urban water use of 9.1 million acre-feet per year (Pacific Institute 2014). Several reports suggest that over half of total residential water use is characterized as outdoor water use with as much as 80 percent in hotter, drier areas of California (DeOreo et al. 2011; Hanak and Davis 2006; Mayer and DeOreo 1999). Outdoor water use includes water used for landscape irrigation, washing cars and impervious surfaces, and evaporation from pools, fountains, and ponds. A recent study by Mini et al. (2014a) has found that outdoor use accounts for 54 percent of total single-family residential water use in the city of Los Angeles. Because outdoor residential water use makes up a substantial portion of the urban water budget, it is important to understand how outdoor use responds to drought events and conservation efforts. However, outdoor use is not often monitored separately in the residential sector and requires detailed data to estimate, which may not be readily available in all regions. For this reason, it is useful to examine other widely-available data that can provide useful information on outdoor water use.

In semi-arid climates, urban vegetation typically consists of non-native vegetation that requires larger volumes of water than what is available through precipitation (Pataki et al. 2011). The high percentage of outdoor residential water use is likely because of high irrigation requirements of typical landscapes on single-family homes in southern California. In Los Angeles, vegetation greenness has been found to be positively correlated with outdoor water use (Mini et al. 2014b). Due to this relationship, studying urban vegetation patterns has the potential to provide valuable insight into drivers of outdoor water use without outdoor consumption data. Several satellite-derived vegetation products exist that provide useful measures for vegetation greenness. Furthermore, these products are readily downloadable and easy to obtain. Because of the observed significance of outdoor use in southern California's urban water budget, understanding how vegetation patterns relate to outdoor consumption is vital to evaluating effectiveness of current water management strategies.

To better understand how changes in water policy and drought events impact urban vegetation, we investigated vegetation patterns across six water districts in coastal southern California. In the analysis, we used NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) normalized difference vegetation index (NDVI) and land cover data to evaluate patterns over varying land cover classifications within the different water district boundaries. Additionally, sector water use data was obtained from three of the six water districts for comparison with the observed vegetation patterns.

Water consumption in the arid and semi-arid regions of the United States has been the focus of recent research. Mini et al. (2014a; 2014b) developed a model to estimate outdoor irrigation, identified drivers of outdoor water consumption, and found that vegetation and outdoor use are positively correlated in Los Angeles. Johnson and Belitz (2012) proposed a method to estimate outdoor water use using remotely-sensed NDVI, calibrated for Los Angeles using household water-delivery records, endmember delineations, and climatic data. These studies contribute to the understanding of vegetation and outdoor use but require detailed mapping of endmember delineations. This often requires use of existing datasets that may not be readily available in all areas or that delineations be hand-digitized using high resolution aerial imagery, which can be an extensive undertaking for large study areas. Additionally, few studies exist that

examine vegetation trends on a regional scale, while many studies are focused in a single municipality or agency. A study by Jenerette et al. (2013) that did analyze vegetation on a regional scale examines the effects of urbanization on vegetation, vegetation sensitivity to income distribution, and variation across seven metropolitan regions in the southwestern United States. However, while their study did test for consumption as a potential correlate for vegetation greenness, they did not examine the effects of conservation efforts on vegetation and consumption. While some studies have attempted to quantify water savings from conservation efforts or pricing (Arbués et al. 2003; Haque et al. 2014), no current literature exists that evaluates the effects of conservation measures on urban vegetation. The current study is unique in that it provides a useful method to compare vegetation patterns to water consumption using data that is readily available with minimal processing while relating vegetation and consumption patterns to recent drought and conservation efforts.

The purpose of this study is to identify general patterns in vegetation that will provide useful information on outdoor water consumption in southern California. Trends are compared across the different water districts to evaluate vegetation and consumption response to various conservation efforts within the semi-arid climate of coastal southern California. After examining vegetation patterns on a regional scale, they are compared to sector water use data from districts with available data. The following research questions are explored: 1) Are there patterns in urban vegetation across southern California and how do they relate to various water use sectors? 2) Can we identify patterns in vegetation greenness related to drought or conservation using NDVI as a proxy for outdoor water use? 3) How does urban greenness respond to climate, i.e. precipitation and temperature? and 4) What drives urban vegetation greenness in southern California?

While this study focuses on water districts in southern California, the research objectives are relevant to utilities and water management agencies in the arid and semi-arid regions of the United States. The ultimate goal of this study is to improve understanding of the response of water demand to drought and conservation measures, with the hope that results will aid water management agencies in the implementation of

effective conservation strategies across southern California and other semi-arid climate regions.

## CHAPTER 2 STUDY AREA

Six water districts from three counties were selected to study urban vegetation patterns in coastal southern California. In Los Angeles County, the selected water districts were Las Virgenes Municipal Water District and the city of Los Angeles. In Orange County, the selected water districts were the city of Huntington Beach, Mesa Water District, and Irvine Ranch Water District. Finally, the city of San Diego was selected for San Diego County. The six water districts were selected to study varying water conservation efforts in areas that share similar climatology. Additionally, each of the study districts are diverse in terms of amount of urbanization, population, income, and water use patterns. Figure 1 contains a study area map that delineates each of the water districts in this study. The data presented in the following sections were collected from the 2010 Urban Water Management Plans for each district (City of San Diego 2011; LADWP 2011; Lippman and Wiersema 2011; Malcolm Pirnie, Inc. 2011; PSOMAS 2011; Welch 2011).

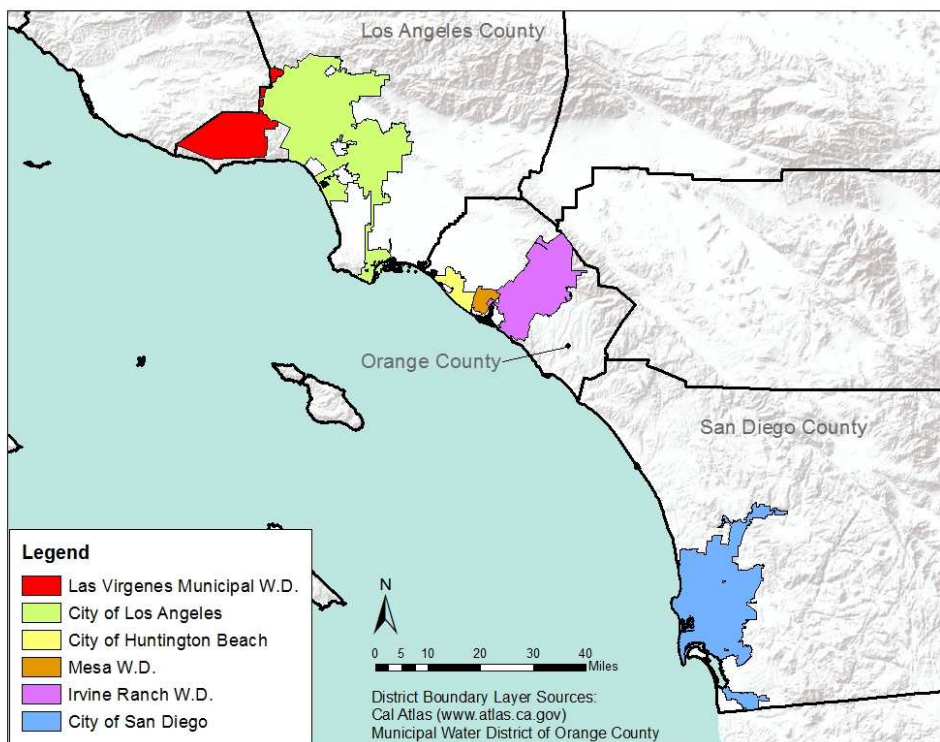


Figure 1. Study Area Map

## 2.1 Study Area Characteristics

The six water districts vary significantly in variables such as service population, percent of urbanization, land cover classification, and average precipitation. Los Angeles and San Diego have the largest service areas of the six districts of approximately 302,644 acres and 201,770 acres, respectively. Huntington Beach and Mesa Water District have the smallest service areas, 17,472 acres and 11,520 acres, respectively. Las Virgenes Municipal Water District and Irvine Ranch Water District have moderately sized service areas but have the largest amount of undeveloped open space. Los Angeles had the largest population of over 4.1 million people followed by San Diego at 1.3 million people. Las Virgenes Municipal Water District has the lowest population of 75 thousand people despite Mesa Water District having the smallest service area. This is due to small percentage of developed land at 14 percent of the total service area. Although all districts are located in the same semi-arid Mediterranean climate of southern California, each experiences variable precipitation likely due to the effects of orographic lifting. Las Virgenes, Los Angeles, and Irvine Ranch experience the highest annual precipitation averages of 16.8 inches, 15.6 inches, and 14.2 inches respectively, due to the large amount of high elevation undeveloped land that typically receives more precipitation. Huntington Beach and San Diego experience considerably less precipitation on average due to being located primarily in low-lying flat land. All estimates for service area characteristics were obtained from the 2010 Urban Water Management Plans reported by each water district and are shown in Table 1. The percentages of land cover classifications for each district is presented in Figure 2.

## 2.2 Water Use

The six water districts also vary widely in water use patterns. Several factors may contribute to differences in water use patterns experienced by each of the districts. Income is shown to be a driving factor of water use in several semi-arid cities (Jenerette et al. 2013; Mini et al. 2014b). Other factors, such as education, ethnicity, amount of precipitation, and temperature, may also contribute to differences in water use. Because

each of the study areas have been found to vary widely in socio-demographic and economic characteristics, it is expected that water use patterns should also vary across districts.

Los Angeles is by far the largest user of water in terms of total water consumption. In 2010, Los Angeles used over 545,000 acre-feet in total with the next highest being San Diego at over 162,000 acre-feet. The total use by Las Virgenes Municipal Water District in 2010 was the least of all the districts at over 18,000 acre-feet, primarily due to temporary restrictions implemented in that year (projected water use if no restrictions were implemented was estimated to be about 26,000 acre-feet). The next lowest water user was Mesa Water District at 19,400 acre-feet.

More information on outdoor water use can be deduced from looking at per capita water use instead of total water use. While Las Virgenes Municipal Water District had the lowest total water use in 2010, per capita water use was the highest among the water districts at 220 gallons per capita per day (GPCD). Los Angeles, while having the highest total use, was the second lowest per capita water user at 119 GPCD. Furthermore, the amount of water used for residential purposes varies significantly. While Irvine Ranch Water District has the second highest per capita use of 205 GPCD, when looking specifically at residential use, Irvine Ranch experiences similar residential use to Los Angeles at 84 GPCD. This suggests that Irvine Ranch Water District may use a greater percentage of water use for public landscaping, such as parks and golf courses, or commercial purposes. Water use data for each district is tabulated in Table 1.

### 2.3 Conservation Efforts in Study Period

Several conservation measures have been implemented in the water districts during the study period. Additionally, these conservation efforts differ widely in scale, implementation, and targeted water use. The variation in conservation measures across districts allows for the evaluation of a diverse collection of conservation strategies.

Several conservation measures have been implemented across the region that focus on reduction in indoor water consumption. While reductions in indoor use would not have an impact on urban vegetation, it would have an impact on total residential water use. Many of the measures aimed at reduction of indoor use involve replacement of old appliances with high-efficiency alternatives. Los Angeles has participated in low-flow shower head and toilet installation programs since the early 1980s and have offered residential high-efficiency clothes washer rebates since 1998. Almost all water districts have implemented high-efficiency appliance installation programs aimed at reducing indoor use.

However, there has been a recent shift in focus of conservation efforts from indoor use to outdoor use. Several types of conservation measures have been implemented after 2000 targeting outdoor residential water use. These conservation measures have the greatest potential to affect urban vegetation. Many of the recent conservation measures are implemented as rebate and discount programs for turf grass replacement, xeriscaping, and artificial turf. Others measures encourage reductions in outdoor use through rebates on high-efficiency and weather-based sprinkler systems, soil moisture sensors, and residential rain barrels.

*Table 1. Study Area Characteristics from 2010 Urban Water Management Plans*

Water District	Service Area (acres)	Population	Precipitation (inches)	Total Water Use (acre-feet)	Water Use (GPCD)	Residential Use (GPCD)
LVMWD	74,640	75,384	16.8	18,591	220	181
LA	302,644	4,100,260	15.6	545,771	119	79
HB	17,472	204,831	11.1	27,268	116	88
MWD	11,520	111,166	13.8	19,400	156	91
IRWD	115,840	338,000	14.2	77,830	205	84
SD	201,770	1,324,305	10.1	162,291	109	67

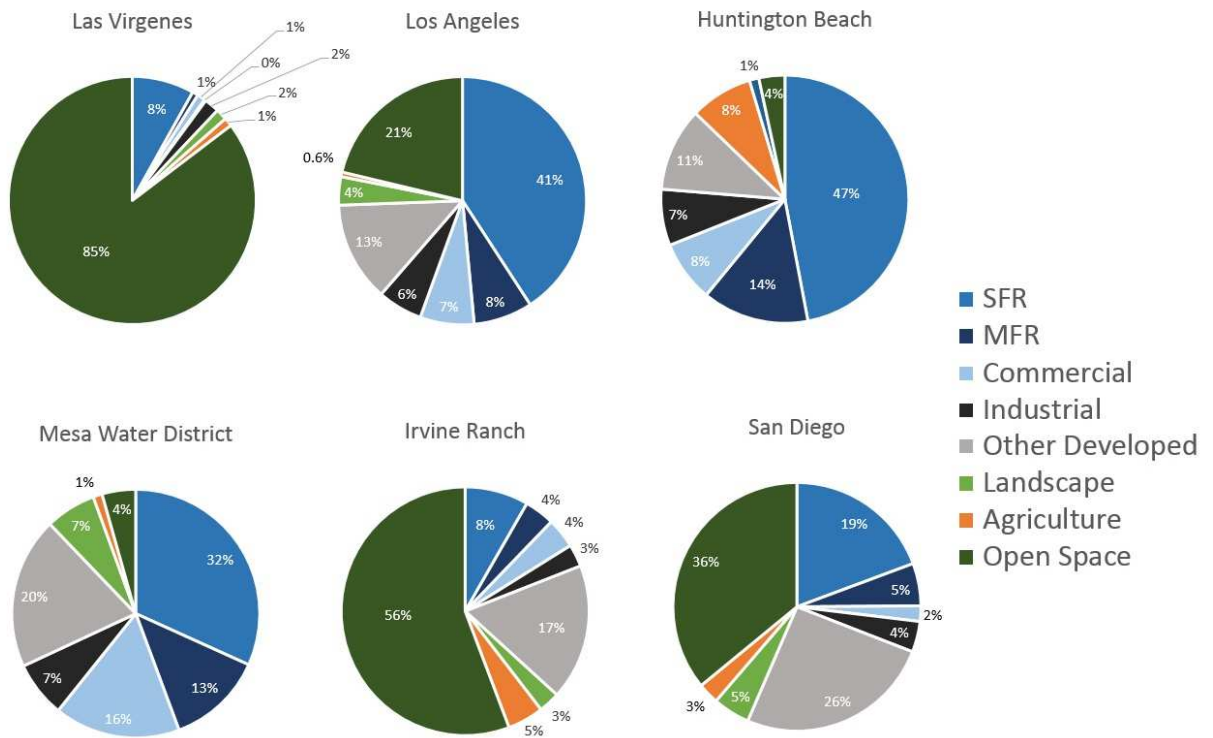


Figure 2. Land cover breakdown for each water district

## CHAPTER 3 DATA

The normalized difference vegetation index is calculated from a normalized transform of the near infrared and red reflectance ratio and provides a measure for photosynthetic productivity of vegetation (Sellers 1985). While many vegetation indices exist, several studies have shown that NDVI is well suited for use in semi-arid regions. NDVI experiences a greater range of values in semi-arid regions when compared to another index, the enhanced vegetation index (EVI) (Huete et al. 2002), making it more sensitive to changes in vegetation. NDVI is also found to be more sensitive in areas with sparse vegetation density (Jackson and Huete 1991), which is typical in semi-arid and urban landscapes. NASA's MODIS NDVI product was selected to analyze vegetation greenness for this study. Specifically, data was obtained from the MOD13 and MYD13 products from NASA's Terra and Aqua satellites. Each satellite collects images at a 250-meter resolution every 16 days on an alternating 8-day schedule. Use of both MOD13 and MYD13 products allowed for a higher temporal resolution than other remote-sensing products. While NDVI can be derived from the USGS Landsat multi-spectral satellite imagery at 30 meters every 16 days, the higher temporal resolution of MODIS allowed for more data points to be used in the timeseries analysis. Additionally, MODIS provides a high quality-controlled dataset that can be readily used by water utilities, while Landsat requires several additional stages of processing.

For precipitation data, the Oregon State University Parameter-elevation Regressions on Independent Slopes Model (PRISM) was used. PRISM is a model that provides a spatial gridded dataset of precipitation and temperature calibrated using climate data from point sources like weather stations and a wide range of physiographic variables (Daly and Bryant 2013). For this study, monthly precipitation and monthly mean temperature was used at a 4 kilometer spatial resolution. Spatial precipitation data allowed for precipitation estimates averaged over each district instead of from several point measurements, which is important in the study areas that are fairly heterogeneous with regards to land cover and elevation. This is especially important in Los Angeles, where much of the urbanization is found in the low-lying lands that receive considerably less precipitation than undeveloped open space at higher elevation.

The water district boundaries were obtained in ESRI shapefile format from the Cal Atlas geodatabase ([www.atlas.ca.gov](http://www.atlas.ca.gov)), with the exception of the three water districts from Orange County. Huntington Beach, Mesa Water District, and Irvine Ranch Water District boundaries were obtained directly from the Municipal Water District of Orange County as ESRI shapefiles. Land cover classification shapefiles were obtained from the Southern California Association of Governments (SCAG) for all districts except for San Diego. San Diego land cover data was obtained from the San Diego Association of Governments (SANDAG). These land cover data sources were chosen over the National Land Cover Database (NLCD), which is a 30 meter resolution raster dataset, because SCAG and SANDAG land cover classification descriptions were more easily relatable to water use sector classifications used by water utilities. In other words, the single-family residential land cover classification from SCAG and SANDAG could be more easily compared to single-family residential water use than the low-intensity developed classification from NLCD. The land cover shapefiles are mapped at a minimum 2 acre (~ 90 meter) resolution from aerial imagery.

Water consumption data was provided by three of the six water districts, the city of Los Angeles, the city of Huntington Beach, and Mesa Water District. Los Angeles monthly water use data by sector was provided by the Los Angeles Department of Water and Power (LADWP) from Fiscal Year 2001 to 2013. Annual water use data by sector was provided by Huntington Beach and Mesa Water District from Fiscal Year 2002 to 2014. Because Los Angeles was the only water district to provide sector use on a monthly timescale, much of the focus on the water consumption comparisons is on Los Angeles water use.

The Palmer Drought Severity Index (PDSI) was used to evaluate the impacts of drought on urban vegetation. PDSI is a complex drought index that utilizes precipitation, temperature, soil moisture, and other data to estimate water supply and demand. The PDSI dataset used in this analysis is on a monthly time scale and is available through the National Climatic Data Center (NCDC). PDSI is calculated regionally according to NCDC climate regions. All districts in this study fall within the South Coast climate region in California. Therefore, the drought index timeseries is the same for all water districts in this study.

Table 2. Data Description

<b>Normalized Difference Vegetation Index (NDVI)</b>	
Source	NASA MODIS (MOD13/MYD13 products)
Temporal Resolution	8 day
Spatial Resolution	250 meter
Period of Record	Water Year (WY) 2001 - 2014
<b>Water Consumption</b>	
Sources	Los Angeles Department of Water and Power (FY 2001 – 2013)
	City of Huntington Beach (FY 2002 – 2014)
	Mesa Water District (FY 2002 – 2014)
<b>Land Cover</b>	
Sources	Southern California Association of Governments (SCAG)
	San Diego Association of Governments (SANDAG)
<b>Precipitation and Mean Temperature</b>	
Source	Oregon State PRISM
Temporal Resolution	Monthly
Spatial Resolution	4 kilometer
<b>Palmer Drought Severity Index (PDSI)</b>	
Source	National Climatic Data Center
Temporal Resolution	Monthly
Spatial Resolution	California South Coast Hydrologic Climate Region

## CHAPTER 4 METHODS

### 4.1 Identifying Trends in Urban Vegetation

General vegetation patterns were observed before performing in-depth analysis. MODIS scenes of NDVI were averaged annually to examine the annual timeseries and annual change in NDVI. Patterns were also observed over various land cover types. Vegetation patterns were then averaged and examined seasonally. Seasonal NDVI was evaluated by averaging the scenes from three months. Winter was defined as January, February, and March. Spring was defined as April, May, and June. Summer was defined as July, August, and September. Fall was defined as October, November, and December.

The first analysis performed after examining general vegetation patterns was a Seasonal Mann-Kendall trend analysis over the entire period of study from Water Year 2001 to 2014 in order to identify any general trends in urban vegetation greenness. The Seasonal Mann-Kendall trend analysis was selected over a simple linear regression because it takes into account seasonal autocorrelation when testing for significance. SCAG and SANDAG land cover shapefiles were converted to a raster dataset with the same spatial reference and pixel size as MODIS. For each water district, NDVI was averaged over a specific land cover classification. NDVI was then aggregated to a monthly timestep for use in the Seasonal Mann-Kendall analysis. The Kendall package for the statistical computing program R was utilized to perform the Seasonal Mann-Kendall trend analysis. The Kendall tau statistic and significance (p value) is calculated by the R program to identify direction and significance of trends. This was performed for the single-family residential and undeveloped open space land cover classifications.

After identifying significant trends over the entire time period, a “tipping point” analysis was conducted to determine if there were any shifts in vegetation trends during the study period. By examining the entire period, localized trends and potential shifts in vegetation patterns can be overlooked. The “tipping point” analysis determines when a shift occurs. This was achieved by evaluating the trend using the Seasonal Mann-Kendall analysis between the start of the study period and a suspected “tipping point” in

the middle of the study period. This procedure was iterated, selecting a different tipping point for each run. The interval between the selected tipping points between iterations was 12 months. A shift in significance or direction of a trend indicates a potential shift in the vegetation trend. The “tipping point” analysis was conducted to see if a shift in trends coincides with conservation measures or drought.

#### 4.2 Spatial Analysis of NDVI using Difference Maps

While the “tipping point” analysis was used to determine if there were any observed short-term temporal trends, difference maps of NDVI were created to see if there were any spatial patterns related to change in vegetation greenness. Difference maps were produced by averaging each MODIS pixel to an annual value. This was done to mitigate the effect of possible outlier months that may have experienced unusually low or high NDVI when comparing monthly values between two years. After obtaining the annual average of NDVI, the difference was taken between the NDVI values for two years. For this analysis, two maps were created: one to look at change from the start of the study period to the identified “tipping point” and another to look at change from the “tipping point” to the end of the study period. Positive values indicate an increase in NDVI for that specific pixel, negative values indicate decrease, and a value of zero indicates no change.

Maps were created looking only at pixels classified as single-family residential. In order to make any meaningful deductions from this analysis, only pixels of the same land cover classification must be examined since different land cover types typically experience different magnitudes of seasonal variability in vegetation greenness. After identifying localized areas of change, those areas were examined using the Historical Imagery feature in Google Earth to visually identify any drivers for localized change. Additionally, groups of pixels within these localized areas were evaluated for any trends to identify reasons for change. This analysis allows for the identification of neighborhoods that may be experiencing increasing vegetation greenness, which may indicate increased outdoor water use.

#### 4.3 Relating Vegetation Patterns to Consumption, Drought, and Conservation

NDVI was plotted against water consumption to identify any relationships between vegetation and outdoor consumption. Furthermore, the patterns are examined in relation to conservation efforts. NDVI was averaged annually for four urban water use sectors: single-family residential, multi-family residential, commercial, and industrial. Sector water consumption data from Los Angeles, Huntington Beach, and Mesa Water District were also aggregated annually. NDVI versus water consumption was first plotted looking at the four water sectors. Afterwards, single-family residential was examined closer in order to look for potential relationships to conservation efforts that have targeted outdoor use. Annual precipitation data was also compared to water use data to evaluate if residential water use was at all correlated to precipitation amount.

In addition to water consumption, NDVI was also compared to several climate variables. The climate variables used in the comparison are monthly precipitation, mean monthly temperature, and the Palmer Drought Severity Index. This comparison was a preliminary examination of potential predictor variables to be used in a multivariate linear regression model to estimate single-family residential NDVI. Correlation between NDVI and these climate variables were analyzed.

#### 4.4 Multivariate Linear Regression Using Climate Predictors

In order to determine which climatic variables are significant drivers of urban vegetation in the study areas, multivariate linear regression models were developed for each water district using a combination of three climate predictors: monthly precipitation, mean monthly temperature, and the Palmer Drought Severity Index. The use of these variables allows us to determine if one climate variable holds greater influence over residential greenness than another.

Model parameter coefficients were estimated using the MATLAB function, *regress*. The *regress* function uses a least squares fitting method to estimate parameter coefficients. Significance values were calculated for each estimated coefficient. Significance values below 0.05 indicate that a model parameter is a significant predictor of NDVI. Parameters with significance values higher than 0.05 indicate that a parameter

can most likely be removed from the model without significantly affecting its predictive power. Additionally, the coefficient of determination ( $R^2$ ), significance value ( $p$ ), and root mean square error (RMSE) were calculated to compare the effectiveness of each model.

Three combinations of climate variables were used in the regression models. The first model (Model 1) used all three climate predictors, precipitation, temperature, and the drought index. The next model (Model 2) removed the drought index from the predictors, and so only precipitation and temperature were used. The final model (Model 3) removed precipitation as a predictor variable, and so only temperature and drought index were used. The three-model structure was used in order to evaluate the effect of removing one independent variable on the significance of the remaining independent variables. The structure for each of the three models are shown below.

$$\text{Model 1: } NDVI_{SFR} = \beta_0 + \beta_1 precip + \beta_2 temp + \beta_3 PDSI$$

$$\text{Model 2: } NDVI_{SFR} = \beta_0 + \beta_1 precip + \beta_2 temp$$

$$\text{Model 3: } NDVI_{SFR} = \beta_0 + \beta_2 temp + \beta_3 PDSI$$

Significant independent variables will provide information on which climate variables are the most important in predicting residential greenness.

## CHAPTER 5 RESULTS AND DISCUSSION

### 5.1 General Vegetation Patterns and Trend Analysis

Vegetation patterns and trends were examined in four different ways: over various land cover classifications, by examining seasonal variability, by evaluating long-term linear trends, and identifying localized trends through the tipping point. The results from these analyses are presented in the subsequent sections.

#### 5.1.1 Land Cover

General patterns in urban vegetation were examined before performing more rigorous analysis. Figure 3 shows NDVI averaged annually by land cover classification. In general, undeveloped open space tends to be greener than developed land. This is expected because it has the largest amount of vegetation cover compared to developed areas. The one exception is in Huntington Beach, where open space NDVI has values similar to the developed areas. Huntington Beach has the highest percentage of urban land cover compared to the other districts, with open space only accounting for 2 percent of land cover in the district (approximately 257 acres). Due to the lack of open space in Huntington Beach, there may be less vegetation than districts with a higher percentage of undeveloped land. Furthermore, NDVI decreases as development intensity increases. This is because high intensity developed pixels contain a greater percentage of non-vegetated impervious surface.

In addition, open space NDVI experiences greater seasonal variability throughout the year than developed areas. For all districts, the single-family and multi-family residential land cover experiences much less variability from year to year. This is most likely due to irrigation practices artificially increasing NDVI during the dry (summer) months, keeping NDVI relatively constant throughout the year. It may also be muted due to impervious area in the developed pixels. NDVI for impervious surfaces does not change seasonally, thus when NDVI is averaged over the entire pixel, it decreases the seasonal variability. In the Irvine Ranch Water District, other urban landscape

experiences similar variability to the open space land cover, suggesting that the other urban land cover is not regularly irrigated like the residential land cover in that district. Figure 4 shows a timeseries of interannual variability in NDVI by land cover type. This figure highlights the high variability that undeveloped open space experiences in comparison to the other land cover types. It is also evident that all developed land cover types experience nearly the same interannual variability for all districts (except Irvine Ranch where other urban mimics open space).

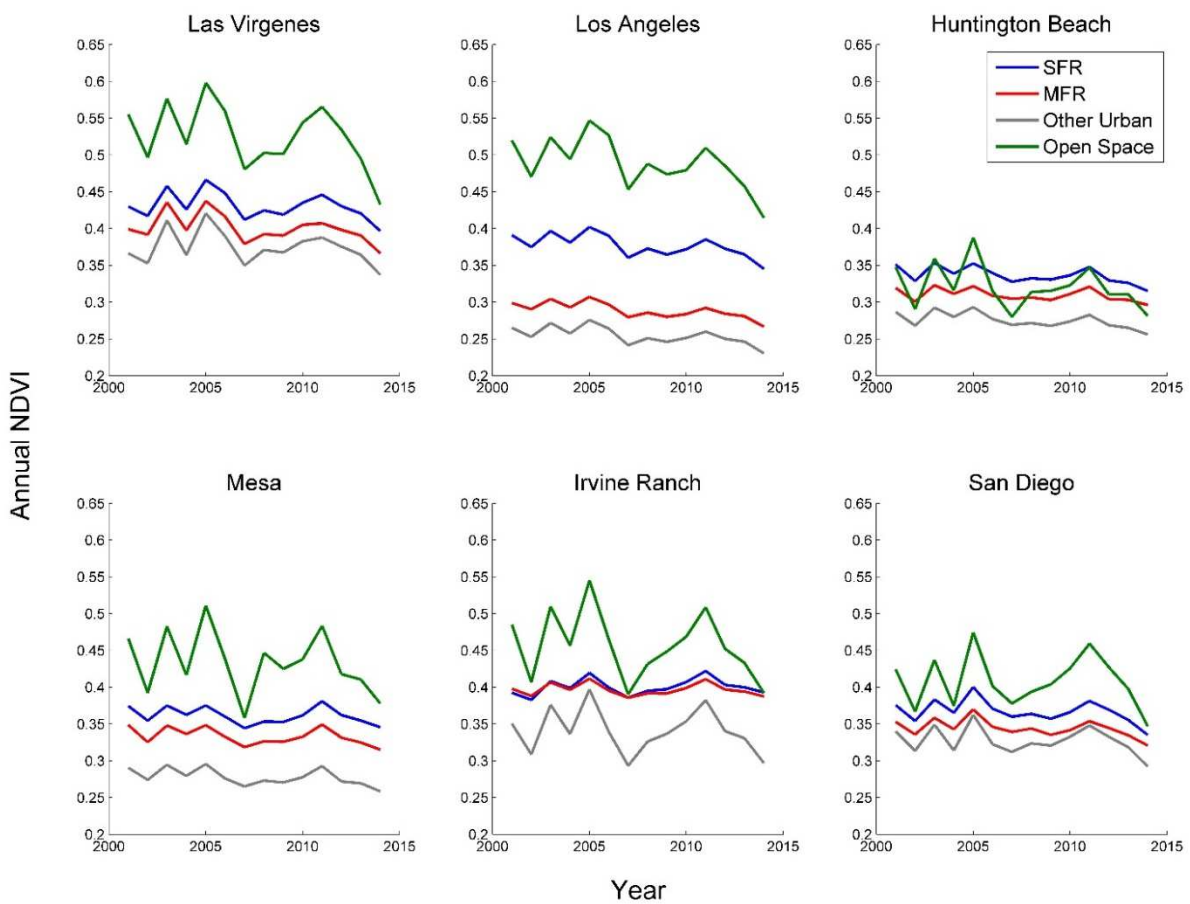


Figure 3. Annual NDVI by Land Cover Classification

### 5.1.2 Seasonal Variability

In addition to looking at annual NDVI by land cover, seasonal NDVI for single-family residential land cover was also examined. Figure 5 shows NDVI averaged over single-family residential area and by season. The majority of the region's precipitation occurs during the wet winter months, while the dry season is during the hotter summer months. For this reason, winter NDVI typically represents the upper limit of NDVI while summer NDVI represents the lower limit. However, in years that experience very low precipitation, the difference between winter and summer NDVI tends to decrease, as observed in the driest year 2007. In 2007, several districts experienced lower winter NDVI compared to summer NDVI. During the years of California's recent drought (2012 to present), seasonal NDVI converges, indicating that drought is influencing seasonal variability.

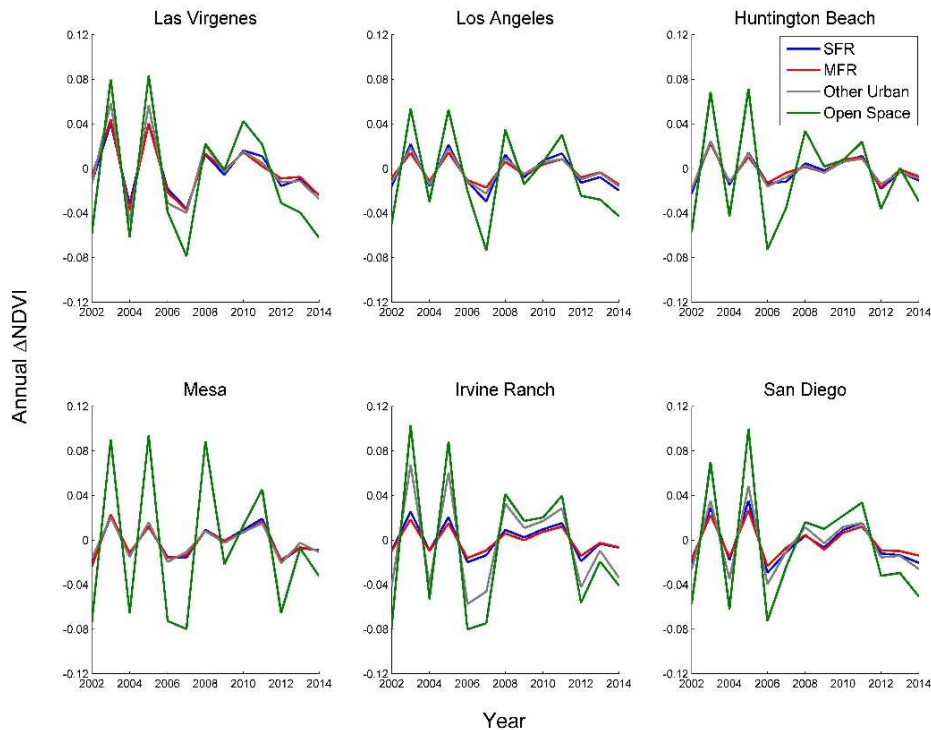


Figure 4. Interannual Variability in NDVI by Land Cover

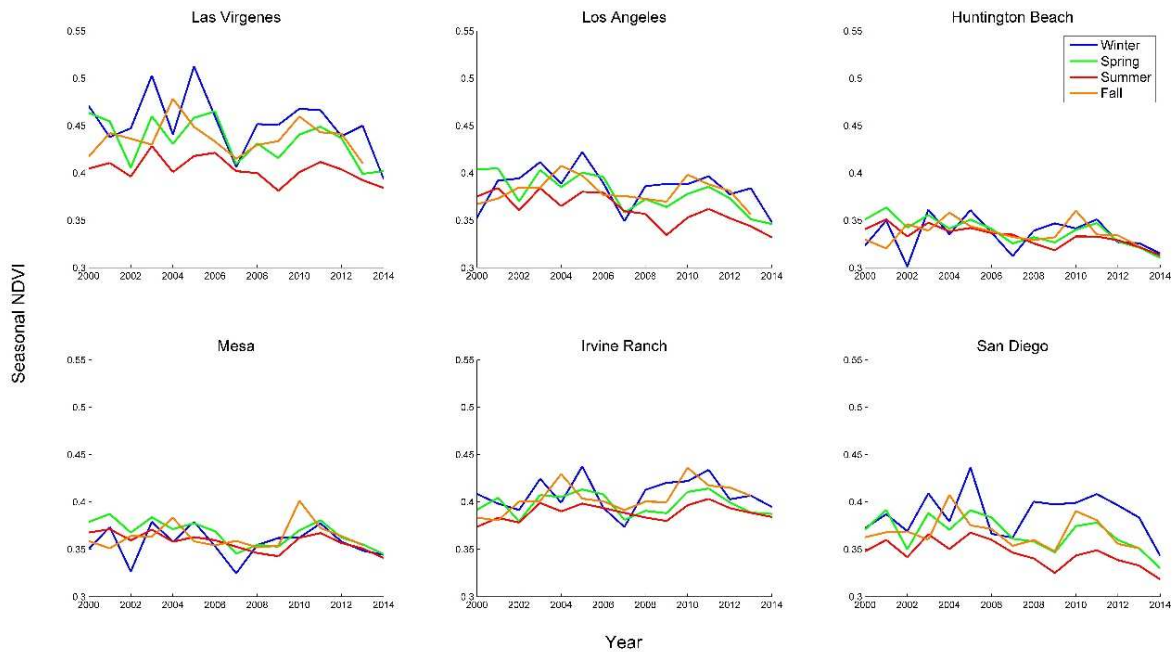


Figure 5. Seasonal NDVI for single-family residential

### 5.1.3 Linear Trend

The results of the Seasonal Mann-Kendall trend analysis are displayed in Table 3 and Figure 6. Table 3 lists the slopes and p-values for each of the trends. The slope was obtained by linear regression while the p-values were calculated using Seasonal Mann-Kendall analysis. Figure 6 shows the timeseries of NDVI for single-family residential plotted for each district from Water Year 2001 through 2014. Based on the results, it appears that residential vegetation patterns are generally decreasing across southern California. For single-family residential, NDVI has a significant negative trend ( $p < 0.05$ ) for all districts except for Irvine Ranch Water District, which exhibits a significant positive trend ( $p < 0.05$ ). The Irvine Ranch Water District has experienced several new single-family developments during the study period. However, because NDVI was averaged over 2001 land use data, new developments were not included in the analysis, indicating that the positive trend is not a result of land use change. Additionally, trends were evaluated for open space NDVI to see if background

vegetation experienced similar trends. The timeseries for open space NDVI are plotted in Figure 7. Significant negative trends were found in all water districts for open space NDVI, suggesting including Irvine Ranch, indicating that background natural vegetation greenness has been decreasing across southern California. Because single-family greenness in the Irvine Ranch Water District is increasing despite decreasing background greenness, it is unlikely that the positive trend is due to climate. It is suspected that the positive trend is related to outdoor irrigation practices to sustain non-native vegetation (i.e. lawns). Further analysis requiring water consumption and conservation data is necessary to identify the drivers behind the observed trends.

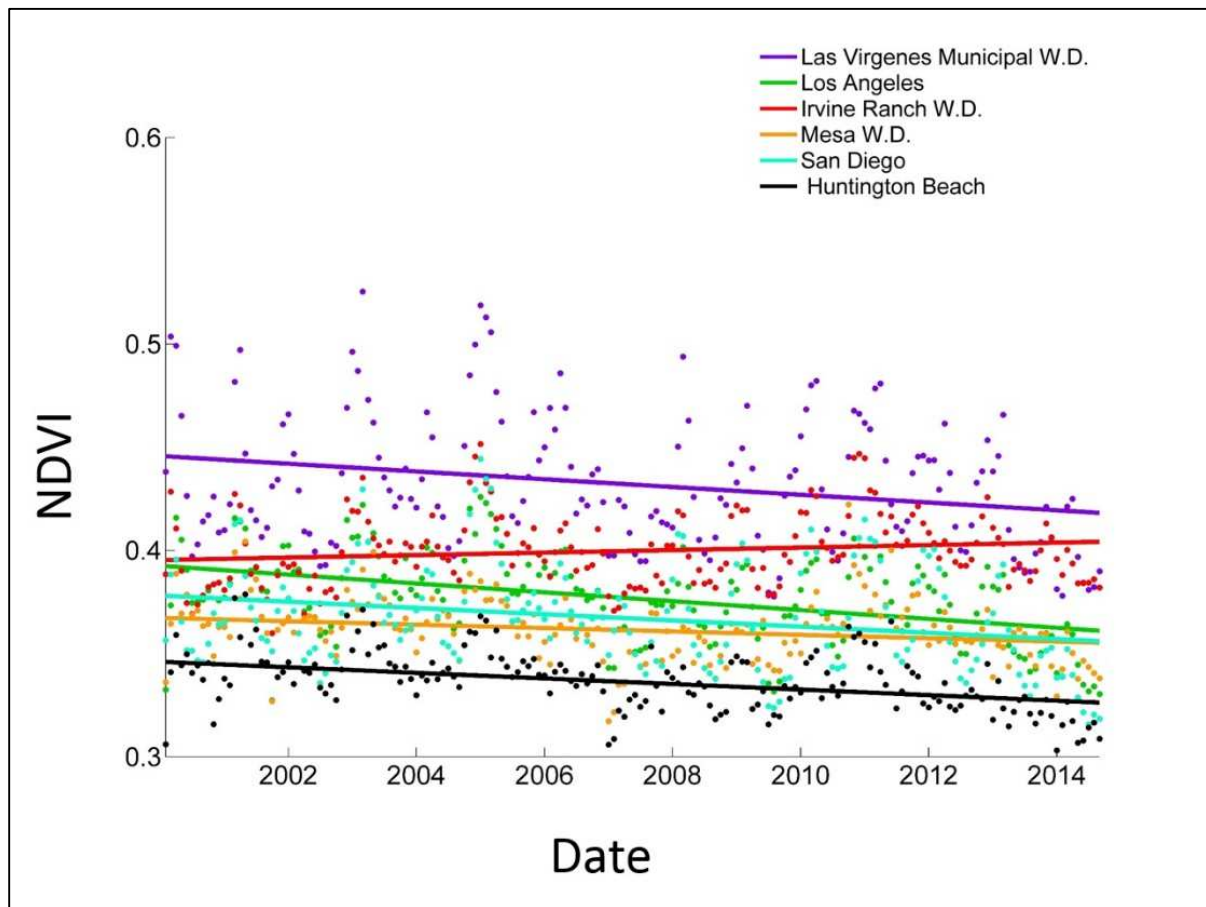


Figure 6. Single-family residential NDVI timeseries by water district

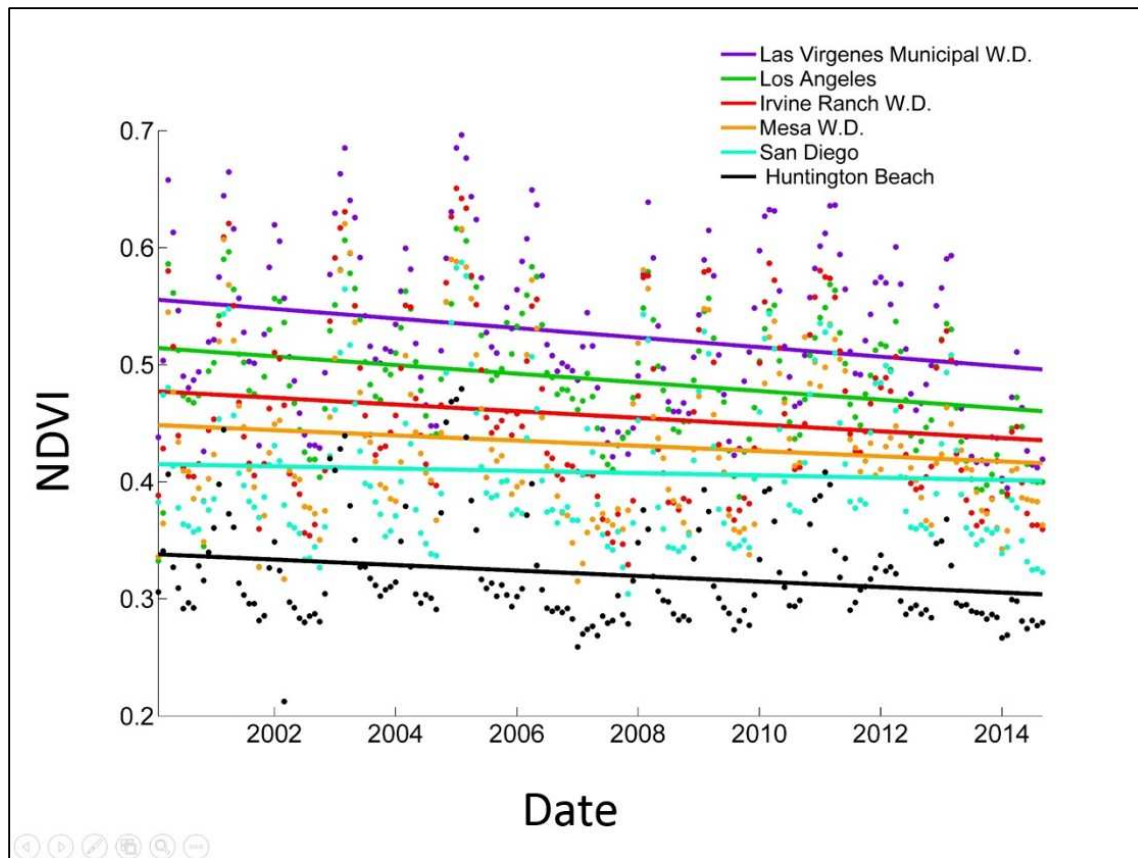


Figure 7. Open space NDVI timeseries by water district

Table 3. Slope and Significance of Vegetation Trends

Water Districts	Single-family Residential		Undeveloped Open Space	
	Slope [yr <sup>-1</sup> ]	p-value	Slope [yr <sup>-1</sup> ]	p-value
LVMWD	-0.0019	0.000	-0.0041	0.001
LA	-0.0021	0.000	-0.0037	0.000
HB	-0.0013	0.000	-0.0023	0.001
MWD	-0.0008	0.000	-0.0022	0.099
IRWD	0.0006	0.008	-0.0029	0.025
SD	-0.0015	0.000	-0.0010	0.114

\* p values highlighted in red indicate significance (p < 0.05)

#### 5.1.4 Tipping Point

After examining general trends in vegetation, additional analysis was used to determine if there is a “tipping point” during the study period when vegetation trends began to change. The intent of this analysis is to determine if the change in vegetation pattern coincides with implemented conservation measures. Figure 8 and Table 4 shows the timeseries with significant trends ( $p < 0.05$ ) and p-values for Los Angeles and Irvine Ranch. The negative trend in Los Angeles was not found to be significant until after Water Year 2008. The tipping point in Los Angeles coincides with the year that water restrictions were implemented within the city. Mandatory restrictions in 2008 were focused on decreasing outdoor water use practices. Since the tipping point coincides with these restrictions, it potentially indicates the effectiveness of those restrictions in decreasing outdoor water use. Additionally, because the tipping point does not occur during the driest year on record (2007), changes in water use practices appear to have a large impact on urban greenness. Aside from Irvine Ranch, the other districts showed similar patterns to Los Angeles.

For Irvine Ranch, a positive trend was present during the first half of the timeseries. However, there is a shift from significant positive to insignificant trend after Water Year 2007. This suggests that while Irvine Ranch’s single-family residential vegetation was increasing at the beginning of the time period, it began to stabilize around the same period as the tipping point in Los Angeles. The results of this analysis highlight the importance of evaluating localized trends in addition to global trends in the data as important shifts in vegetation patterns could be missed.

## 5.2 Results from Spatial Analysis

NDVI difference maps were created to identify areas experiencing large changes in vegetation across single-family residential land cover in hopes of better understanding drivers of increases and decreases in urban greenness. The focus of this analysis is on Irvine Ranch Water District since it was the only district to have a significant positive trend in single-family residential NDVI. Figure 9 shows NDVI difference for single-family residential land cover in the Irvine Ranch Water District

before and after the identified “tipping point” year. The two maps show change in NDVI from 2001 to 2007 and 2008 to 2014, where positive (blue) values indicate an increase in NDVI in that pixel and negative values (red) indicate decrease. The tipping point year was used for comparison to understand the shift in trends observed during the tipping point analysis. The first map shows that instead of uniform increase across the water district, there were localized areas of positive increase that cause the overall positive trend in single-family residential NDVI. Several aerial images were examined to identify drivers of change for those localized areas using the *Historical Imagery* feature in Google Earth. There were no identifiable drivers causing the positive change in these areas using the aerial imagery. Changes in land use classification are most likely not the cause since we only analyzed areas that experienced no land cover change during our study period. The second map, depicting change in NDVI from Water Year 2008 to 2014, shows that change in NDVI was more uniform across the district and that there are fewer localized areas of change.

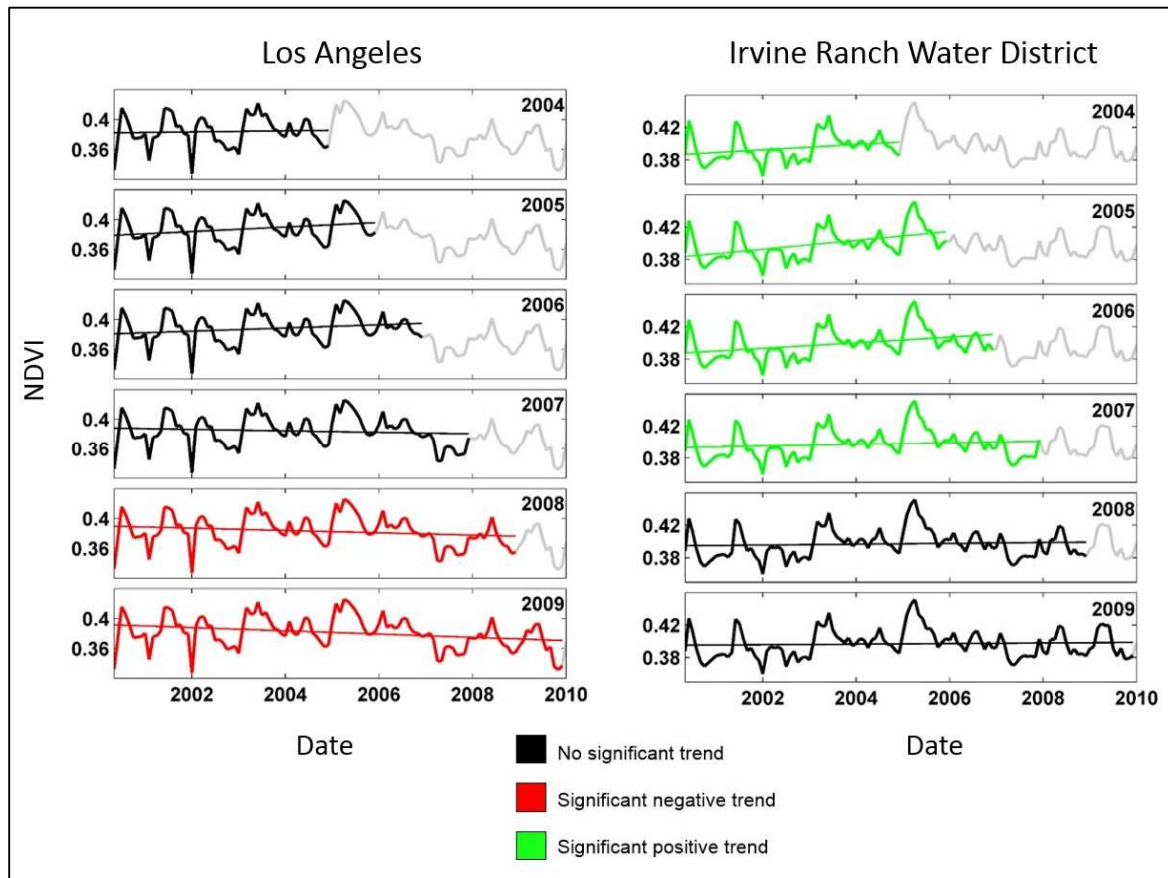


Figure 8. Tipping point analysis for Los Angeles and Irvine Ranch Water District

Table 4. Slope and Significance of Trends in "Tipping Point" Analysis

Tipping Point Year	Los Angeles		Irvine Ranch Water District	
	tau	p-value	tau	p-value
2004	0.039	0.758	0.462	0.000
2005	0.200	0.062	0.562	0.000
2006	0.123	0.196	0.412	0.000
2007	-0.123	0.151	0.195	0.023
2008	-0.225	0.004	-0.135	0.087
2009	-0.286	0.000	0.091	0.214

\* p values highlighted in red indicate significance (p < 0.05)

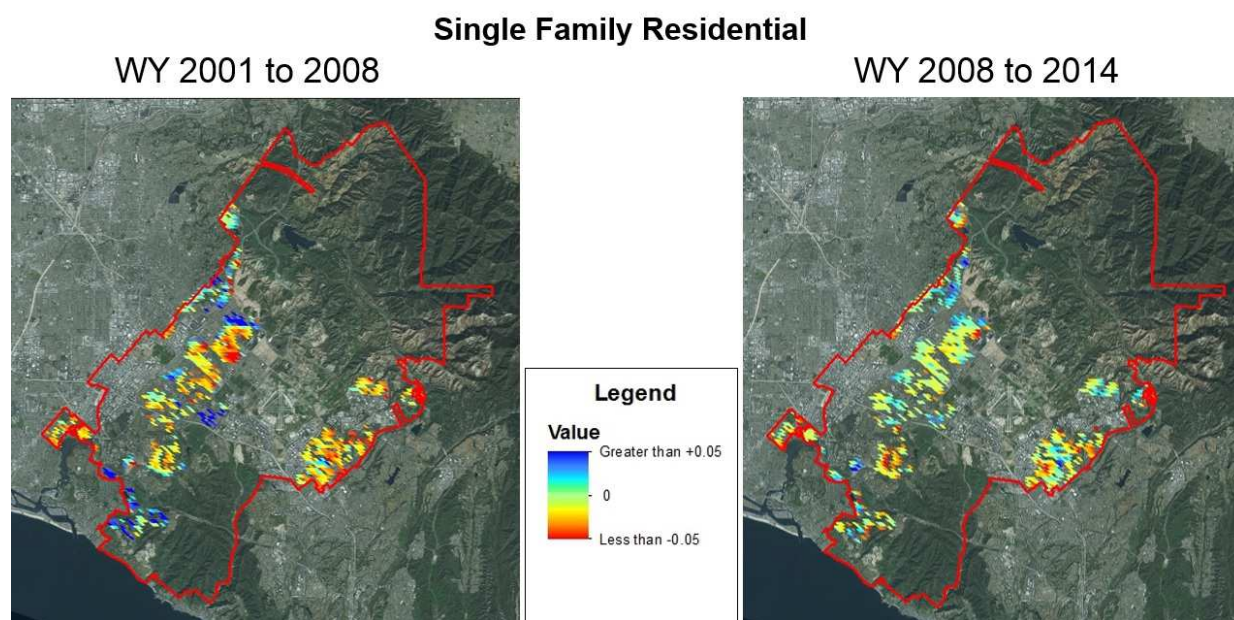


Figure 9. NDVI difference maps for Irvine Ranch Water District

### 5.3 Comparison of Vegetation, Water Consumption, and Climate

Vegetation was compared to annual sector water use for Los Angeles, Huntington Beach, and Mesa Water District. The comparison was made for the single-

family residential, multi-family residential, commercial, and industrial water use sectors. NDVI was evaluated over land use classifications that shared the same description as the water use sectors (i.e. single-family residential water use was assumed to occur exclusively on single-family residential land use). Figure 11 shows NDVI versus annual sector water use for the three districts. There appears to be a linear relation between water use and NDVI, where the highest water users experience the highest NDVI. This potentially indicates that water use is heavily influenced by vegetation and outdoor water use practices. Huntington Beach and Mesa Water District experienced similar patterns. All three water districts showed positive correlation between sector water use and NDVI. Single-family residential sector was the highest water user in Los Angeles and Huntington Beach. However, the multi-family residential sector experienced similar water use levels as single-family residential and was often the highest user in Mesa Water District. This was originally thought to be due to a higher percentage of the population residing in multi-family complexes, but land cover analysis revealed that single-family is the largest residential land cover type in the Mesa Water District. Sector water use could not be normalized by population within each sector due to insufficient data, so total sector water use was used. Population estimates by land cover type are required to investigate this anomaly further.

Because single-family residential sector has a higher percentage of outdoor consumption, approximately 54% of total use according to Mini et al. (2014a), and the largest total consumption of all sectors, it was examined further to evaluate if any patterns were associated with conservation measures implemented during the study period. Figure 12 shows NDVI versus single-family water use for Los Angeles. In Los Angeles, there was clustering of NDVI values for years before and after water restrictions were implemented. NDVI values for years before water restriction implementation (Fiscal Year 2001 to 2006) were higher than values for years during water restrictions (Fiscal Year 2007 to 2009). Additionally, for years during water restrictions, there is a progressive decrease in water use with a considerable drop in 2010. This may be due to the increase in water restrictions over the years. Starting in 2007, LADWP implemented a series of increasing water restrictions targeted at outdoor water use (LADWP 2011). Voluntary restrictions were implemented in 2007, mandatory

restrictions in 2008, and more stringent mandatory restrictions with price increases in 2009. Fiscal Year 2007 received the least precipitation of 110 millimeters during the period of record for the consumption data and had the highest sector water use of approximately 262,000 acre-feet per year. While 2007 was the first year of conservation efforts, homeowners were most likely compensating for the low precipitation by applying additional irrigation to outdoor vegetation. Homeowners likely had to decrease their outdoor water use due to the subsequent mandatory restrictions, leading to the progressive decrease in annual water use after 2007.

Figure 10 shows annual single-family residential water use versus precipitation for Los Angeles, Huntington Beach, and Mesa Water District. Using a significance level of 0.05, there is no significant correlation between annual water use and precipitation in any of the three districts with water use data, indicating that residents in this region do not alter watering practices based on precipitation. Because most precipitation in this region occurs in the wetter winter months while heavy irrigation is applied during the dry summer months, precipitation may not be an accurate indicator for outdoor water consumption. The other two districts were inspected similarly to observe any patterns related to conservation measures. However, no clustering was observed and NDVI was variable for annual precipitation and water use.

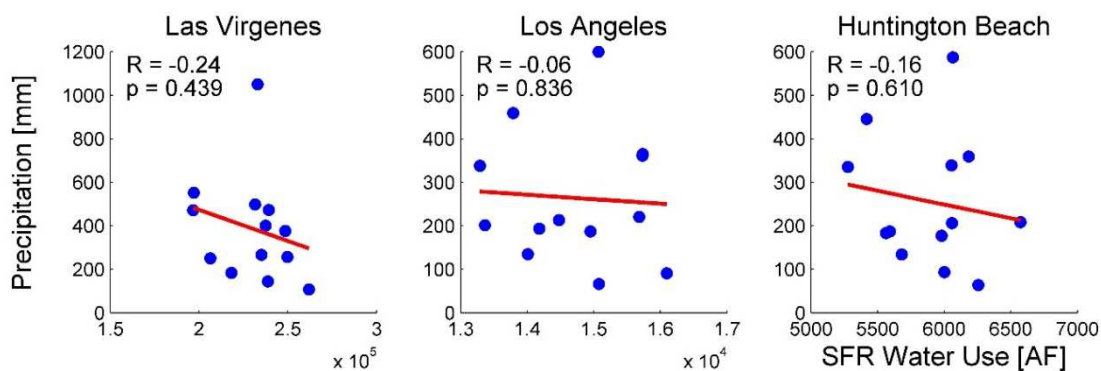


Figure 10. Annual single-family residential water use vs. precipitation

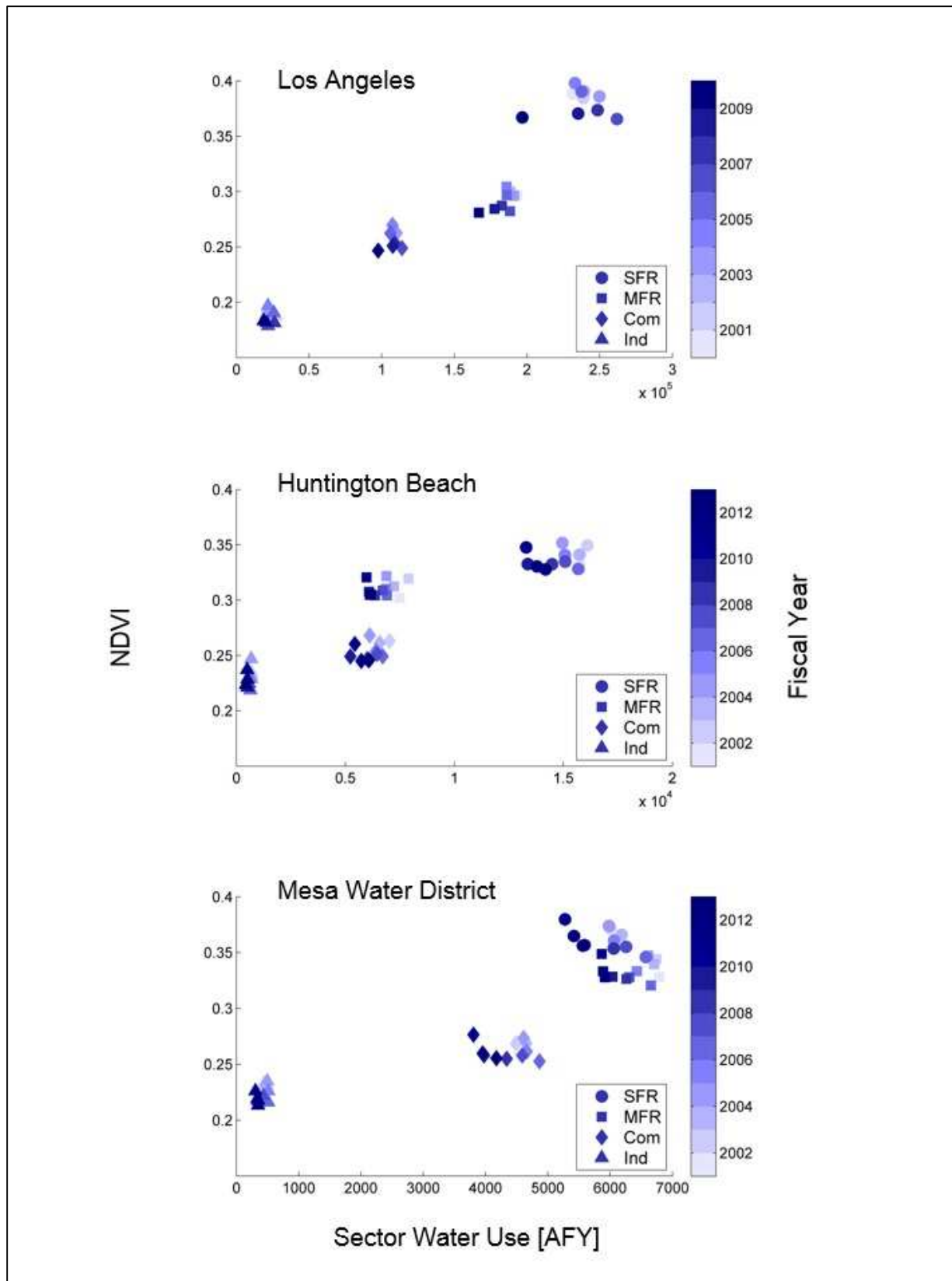


Figure 11. NDVI versus water use by sector

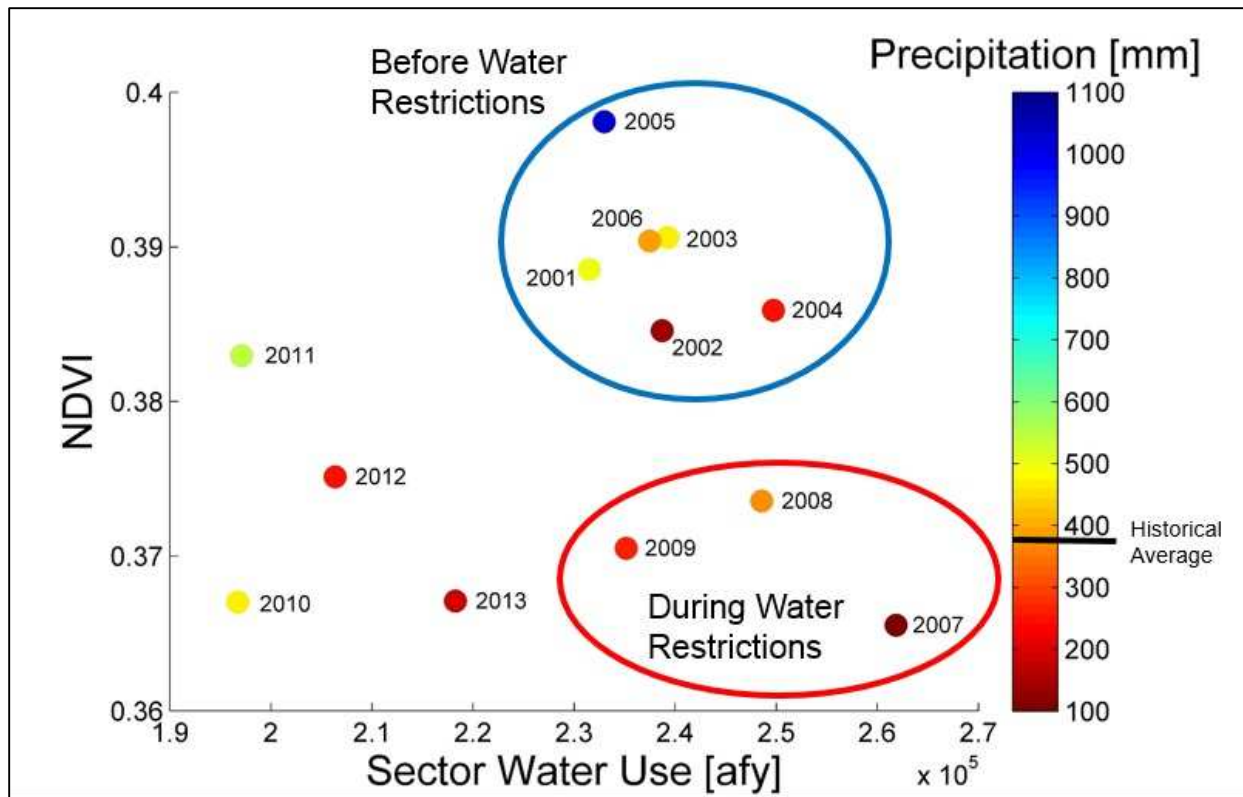


Figure 12. Single-family residential NDVI vs. water use in Los Angeles

#### 5.4 Results from the Multivariate Linear Regression Model

Three models were examined using a combination of three climate predictors: monthly precipitation, mean monthly temperature, and the Palmer Drought Severity Index. The results of the regression in Model 1 showed that precipitation was not a significant predictor of single-family residential NDVI for most districts. Precipitation was only a significant driver of vegetation for Huntington Beach and Irvine Ranch Water District. Temperature was found to be a significant driver in all districts except for Huntington Beach and Mesa Water District. Model 1 also found the Palmer Drought Severity Index to be a significant predictor variable in all six water districts.

Model 2 examined only precipitation and temperature as predictors of residential NDVI. The results from Model 2 indicate that precipitation is a significant predictor variable for all water districts after excluding the Palmer Drought Severity Index.

Because the significance of precipitation changes substantially in all water districts after removing the drought index, multicollinearity is suspected between the two parameters meaning that two or more independent predictor variables may be correlated to some degree. Because the Palmer Drought Severity Index is calculated using estimated water supply and demand estimated from precipitation and temperature, along with several other factors, it is likely that some degree of multicollinearity exists. Temperature coefficients and significance values are not significantly impacted by removing the drought index from the model. Although precipitation is a significant driver in Model 2, the  $R^2$  values are lower and RMSE values higher, suggesting decreased model performance when excluding the drought index.

Because multicollinearity is suspected between precipitation and the drought index, the correlation between the two predictor variables were examined. Significant positive correlations were observed between precipitation and the Palmer Drought Severity Index for all districts. This indicates that higher precipitation months tend to relate to higher PDSI values (water abundance). After examining the correlation between precipitation and PDSI for all months in the period of record, the correlation was examined with only months containing the upper 25<sup>th</sup> percentile of monthly precipitation. The upper 25<sup>th</sup> percentile precipitation months were examined because dry months may not necessarily indicate drought conditions but, rather, the naturally low precipitation during the hotter summer months. When examining only the upper 25<sup>th</sup> percentile precipitation months, the correlation coefficients for each district are higher, suggesting a stronger positive correlation. Additionally, correlation between precipitation and PDSI for all districts were found to be significant at the 0.05 level. Correlations using all months are shown in Figure 13. Correlations using only months containing the upper 25<sup>th</sup> percentile of monthly precipitation are shown in Figure 14.

Model 3 predicts residential NDVI using only temperature and the Palmer Drought Severity Index as predictor variables. Model 3 has similar parameter coefficients and significance values for temperature and drought index when compared to Model 1. Additionally, model performance is not greatly affected by removing precipitation from the model, with the exception of a small but noticeable change in model performance for the water districts that showed precipitation as a significant predictor in Model 1. For

Huntington Beach and Irvine Ranch Water District, where precipitation was found to be significant in Model 1, RMSE increased. The coefficient of determination decreased slightly across all districts. However, because the error did not increase for most districts, Model 3 performs similarly to Model 1. This demonstrates that it is reasonable to replace precipitation with the Palmer Drought Severity Index as a predictor variable for most districts. Table 5 shows a comparison of model performance statistics. Estimated parameter coefficients and significance values are displayed in Table 6. Figures for modeled versus observed values can be found in the appendix.

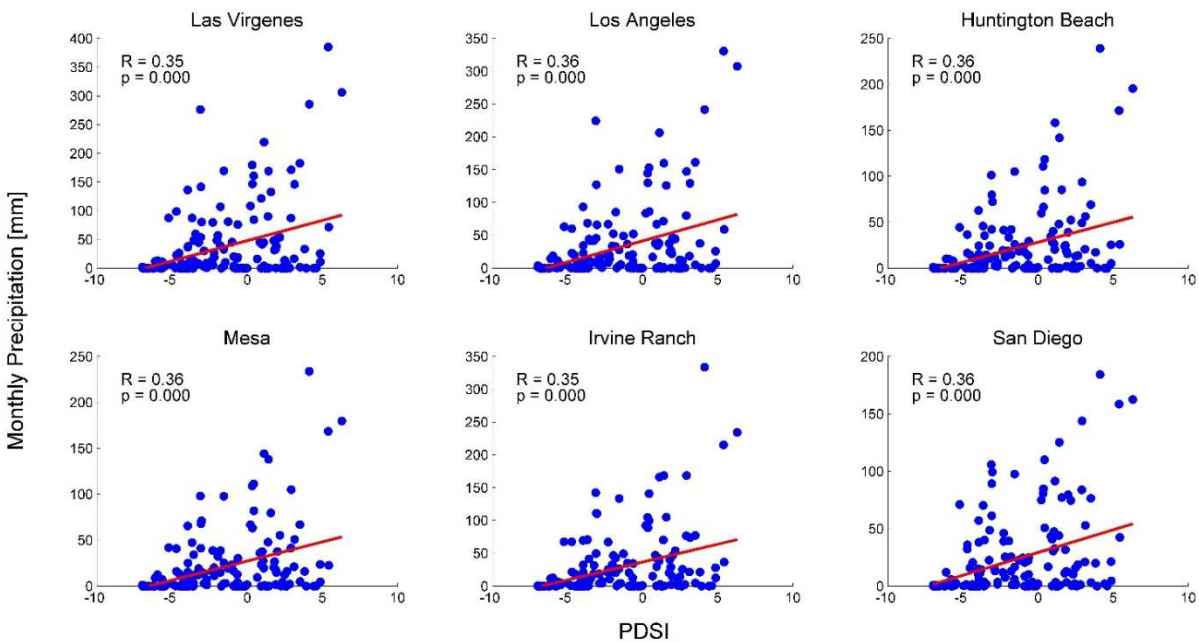


Figure 13. Precipitation-PDSI correlation

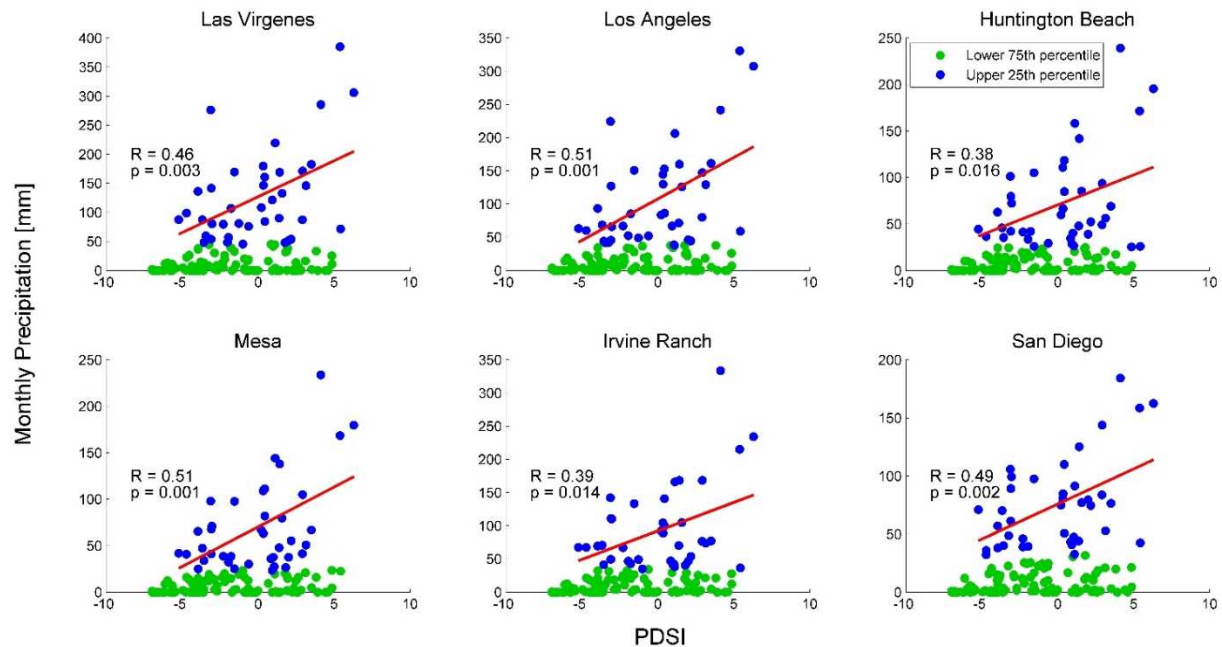


Figure 14. Precipitation-PDSI correlation for 25th percentile monthly precipitation

Table 5. Model Performance Statistics

Water Districts	Model 1			Model 2			Model 3		
	R <sup>2</sup>	p	RMSE	R <sup>2</sup>	p	RMSE	R <sup>2</sup>	p	RMSE
LVMWD	0.531	0.000	0.0210	0.382	0.000	0.0242	0.530	0.000	0.0210
LA	0.518	0.000	0.0141	0.310	0.000	0.0168	0.517	0.000	0.0141
HB	0.317	0.000	0.0118	0.130	0.000	0.0133	0.294	0.000	0.0120
MWD	0.317	0.000	0.0126	0.062	0.008	0.0147	0.313	0.000	0.0126
IRWD	0.459	0.000	0.0126	0.288	0.000	0.0145	0.431	0.000	0.0129
SD	0.647	0.000	0.0146	0.478	0.000	0.0178	0.639	0.000	0.0148

\*Model 1 includes precipitation, temperature, and PDSI variables. Model 2 includes only precipitation and temperature variables. Model 3 includes only temperature and PDSI variables.

Table 6. Estimated Parameter Coefficients for Multivariate Linear Regression

Water District	Model	$\beta_0$ (constant)		$\beta_1$ (precip)		$\beta_2$ (temp)		$\beta_3$ (PDSI)	
		Value	P	Value	p	Value	p	Value	P
LVMWD	1	0.5060	0.000	2.55e-5	0.440	-0.0038	0.000	0.0039	0.000
	2	0.4986	0.000	9.17e-5	0.012	-0.0038	0.000	-	-
	3	0.5111	0.000	-	-	-0.0040	0.000	0.0040	0.000
LA	1	0.4205	0.000	1.23e-5	0.626	-0.0021	0.000	0.0031	0.000
	2	0.4131	0.000	7.73e-5	0.008	-0.0020	0.000	-	-
	3	0.4226	0.000	-	-	-0.0021	0.000	0.0031	0.000
HB	1	0.3405	0.000	6.88e-5	0.026	-5.26e-5	0.888	0.0020	0.000
	2	0.3360	0.000	1.31e-4	0.000	-3.76e-5	0.929	-	-
	3	0.3496	0.000	-	-	-4.73e-4	0.152	0.0023	0.000
MWD	1	0.3611	0.000	3.09e-5	0.361	2.60e-4	0.485	0.0025	0.000
	2	0.3548	0.000	1.13e-4	0.003	3.17e-4	0.466	-	-
	3	0.3649	0.000	-	-	9.12e-5	0.778	0.0026	0.000
IRWD	1	0.4208	0.000	7.14e-5	0.006	-0.0010	0.000	0.0023	0.000
	2	0.4146	0.000	1.28e-4	0.000	-9.68e-4	0.004	-	-
	3	0.4309	0.000	-	-	-0.0015	0.000	0.0026	0.000
SD	1	0.4310	0.000	7.81e-5	0.067	-0.0034	0.000	0.0034	0.000
	2	0.4203	0.000	1.96e-4	0.000	-0.0032	0.000	-	-
	3	0.4400	0.000	-	-	-0.0038	0.000	0.0036	0.000

\* p values highlighted in red indicate significance (p < 0.05)

## CHAPTER 6 CONCLUSION

The results from the analysis of general vegetation patterns and trends provide valuable insight into urban vegetation dynamics in the coastal southern California region. It was discovered that single-family residential vegetation is generally decreasing across southern California. The exception is in Irvine Ranch Water District, where residential vegetation shows a significant positive trend. The tipping point analysis shows that after Water Year 2007, vegetation in Irvine Ranch Water District shifts from a positive trend to no trend. Upon examining the difference maps, it is clear that while average residential vegetation is increasing during the first half of the period (2001 to 2007), the positive trend is being driven by smaller localized areas of change. The use of 2001 land cover data (from the beginning of our study period) ensures that no new residential developments are contributing to the observed increase in NDVI. Water consumption data for Irvine Ranch Water District is needed to better understand the drivers of this increase. Consumption data at the Census tract level may provide insight into why these small localized areas are experiencing greater change than other areas in the district. The use of vegetation difference maps may also aid water utilities in identifying neighborhoods that are increasing in vegetation greenness, potentially indicating an increase in outdoor water use, allowing utilities to target conservation efforts at high outdoor water users or find neighborhoods not adhering to mandatory conservation measures.

For the districts with available water use data, consumption and vegetation greenness were compared to identify any patterns related to recent conservation measures. While, Huntington Beach and Mesa Water District did not experience any identifiable patterns related to conservation efforts, conservation efforts in Los Angeles were shown to have an effect on urban vegetation and consumption. When comparing sector consumption data to NDVI, all three districts analyzed were clustered by sector and displayed positive correlation between total sector use and NDVI. This suggests that substantial percentage of consumption in high water use sectors may be due to irrigation. In general, single-family residential used the most water, followed by multi-family residential, commercial, and then industrial. The one anomaly was in Mesa Water

District where the highest water use sector was multi-family residential. In order to explain this anomaly, population estimates in the multi-family residential sector are needed to determine if the high use is due to greater per capita use or if there is a greater percentage of the population residing in multi-family complexes. Closer inspection of single-family residential NDVI versus water use in Los Angeles resulted in clear clustering of points for years before and during water restrictions. Years before water restrictions had higher NDVI values and water use, while years during and after mandatory restrictions resulted in lower NDVI values. Additionally, years during water restrictions show progressively decreasing water use coinciding with stricter water restrictions, indicating that the restrictions did have an impact on outdoor water use practices.

In order to determine the drivers of urban vegetation in southern California, multivariate linear regression models were developed using climatic predictor variables. We wanted to determine if precipitation or temperature has an effect on residential greenness and whether or not drought conditions affect residential greenness, and relatedly, outdoor water use. From the three models using different combinations of predictor variables, we found that the Palmer Drought Severity Index predicted greenness with more accuracy than precipitation. Precipitation was not found to be a significant predictor variable for most districts until the drought index was removed from the model. The lack of significance of precipitation on urban greenness may suggest that residents are not altering irrigation practices in response to precipitation. The inclusion of the drought index improved performance of the model and was found to be significant across all water districts. This indicates that drought does have a significant relationship to residential vegetation and possibly outdoor use. Plotting the relationship between NDVI and the drought index shows a positive relationship, meaning months with higher drought severity (a negative index) indicates that greenness is lower. Temperature was also found to have a significant relationship to residential greenness in most districts. This coincides with the fact that irrigation requirements increase during the hotter summer months in southern California.

Results show that urban vegetation experiences high variability, between different water districts and even within a single district. Additionally, the results found

that urban vegetation is influenced by many factors. The results from the multivariate models show that important driving factors include temperature and drought. In general, precipitation was not a significant driver of urban greenness. This potentially indicates that homeowners are not altering outdoor irrigation practices to account for precipitation. Using this information, water districts can make the decision to focus on conservation measures that don't require residents to actively conserve but instead implement conservation measures that passively save water, like turf removal and xeriscaping. The analysis of vegetation trends and spatial patterns can aid water utilities in targeting trouble areas and use resources more effectively to implement conservation measures.

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## APPENDIX

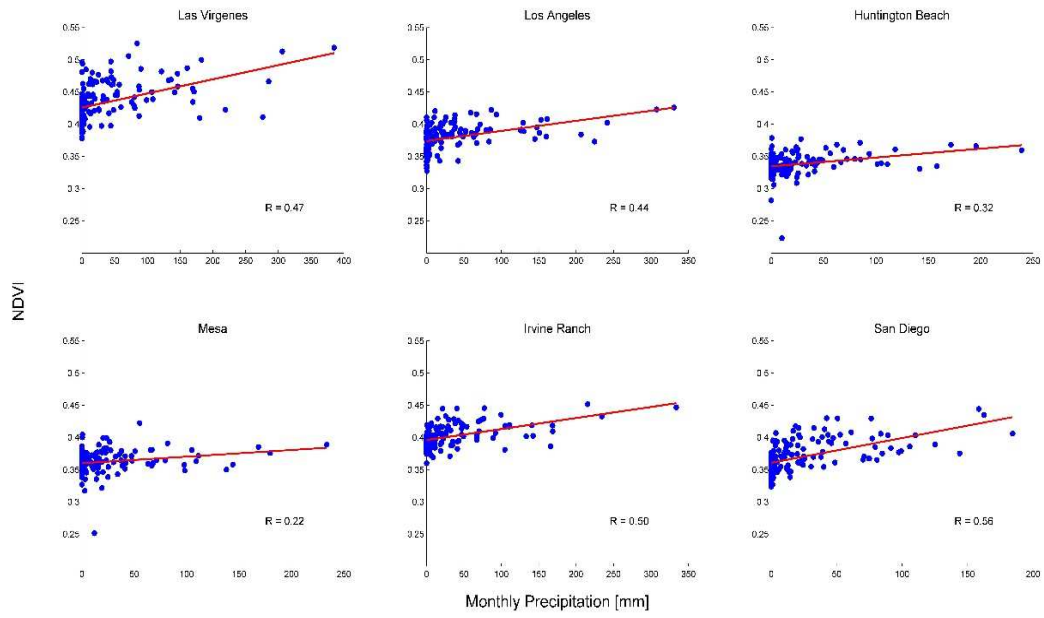


Figure A.1. NDVI vs. Precipitation

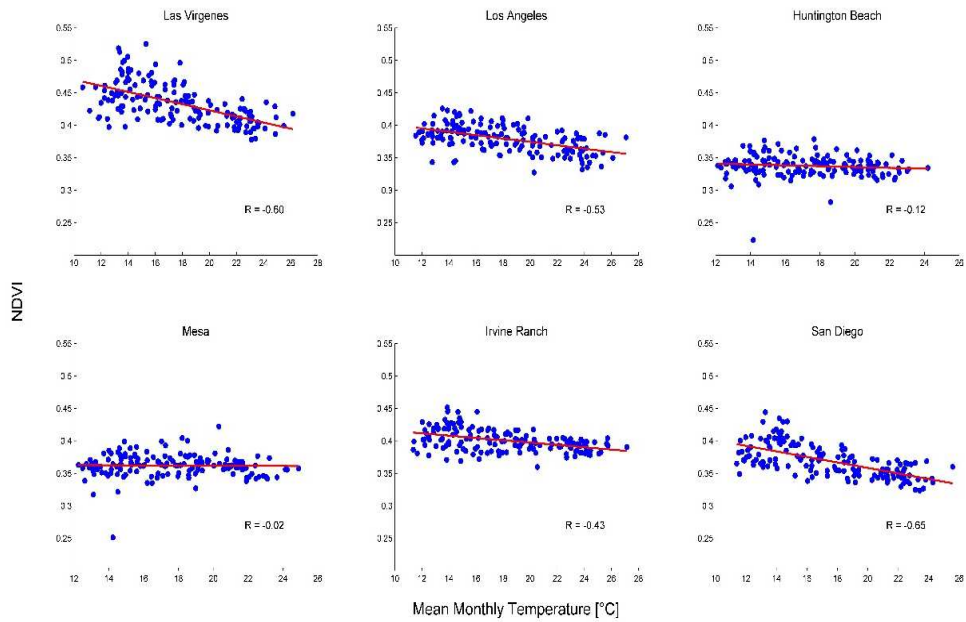


Figure A.2. NDVI vs. Temperature

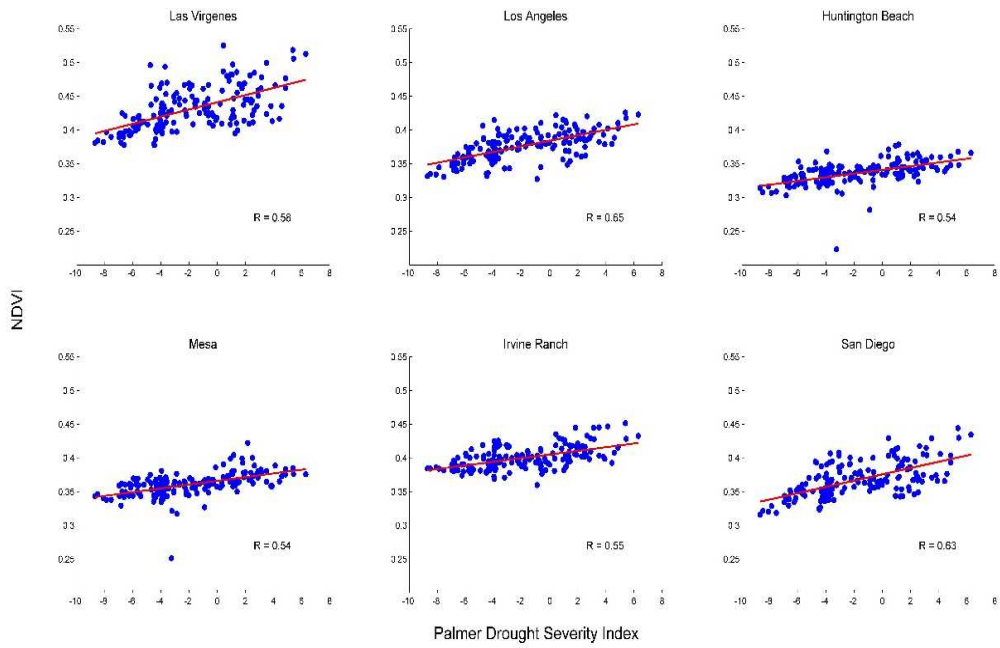


Figure A.3. NDVI vs. Palmer Drought Severity Index

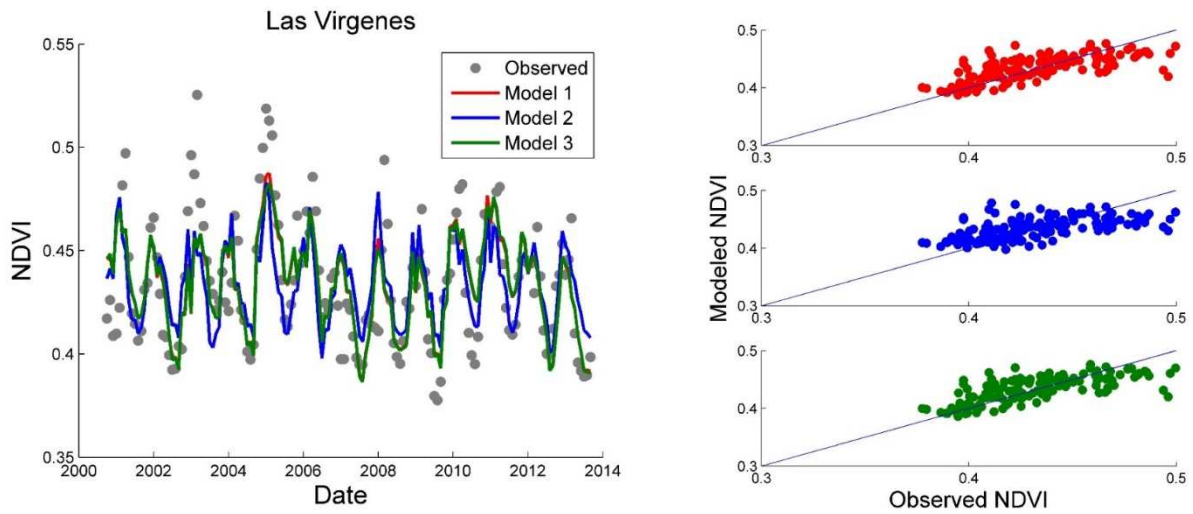


Figure A.4. Las Virgenes Model Results

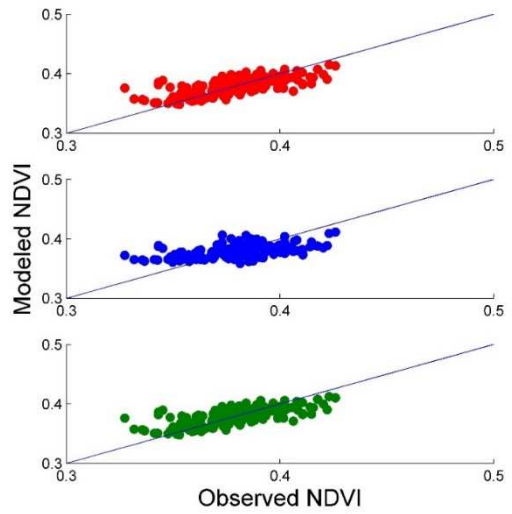
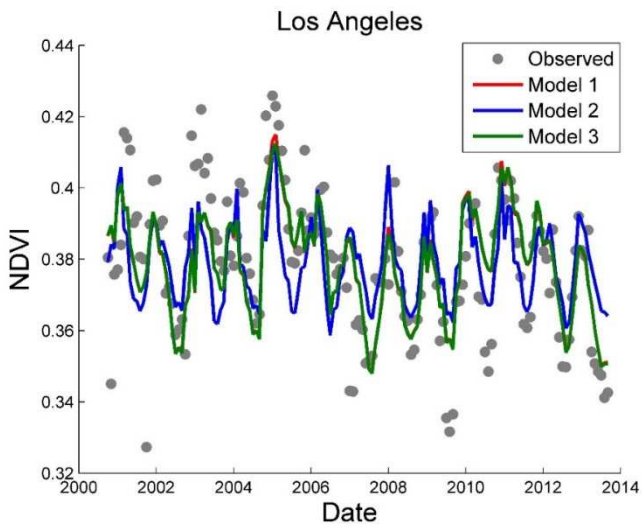


Figure A.5. Los Angeles Model Results

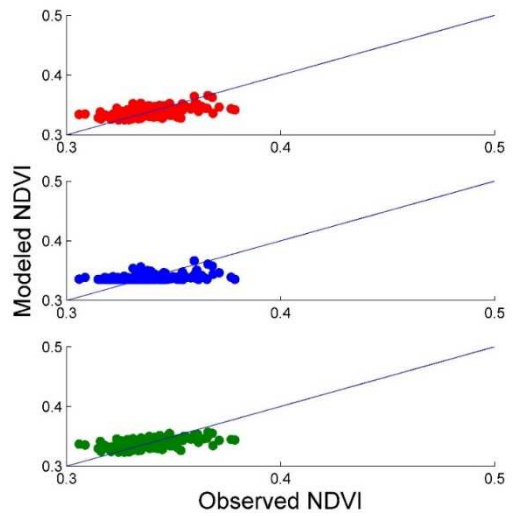
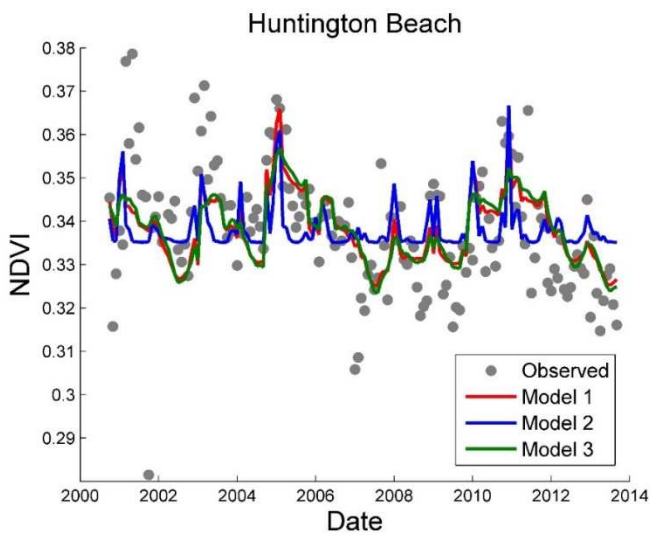


Figure A.6. Huntington Beach Model Results

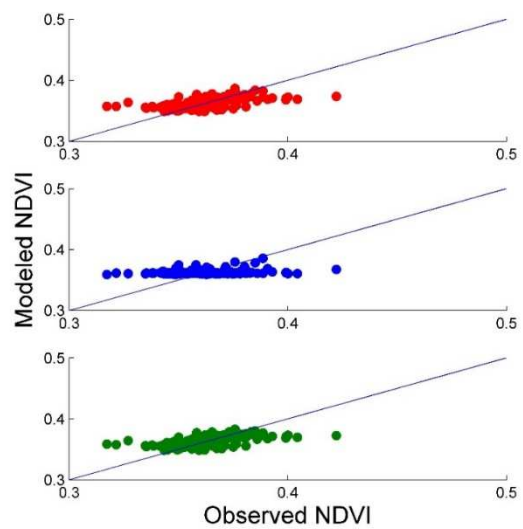
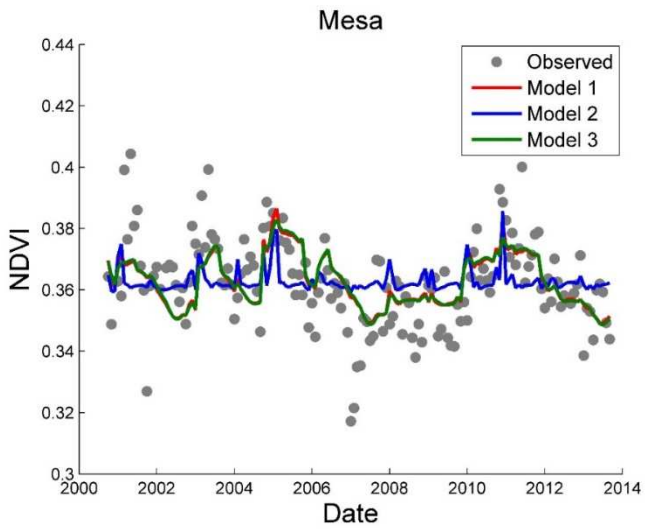


Figure A.7. Mesa Water District Model Results

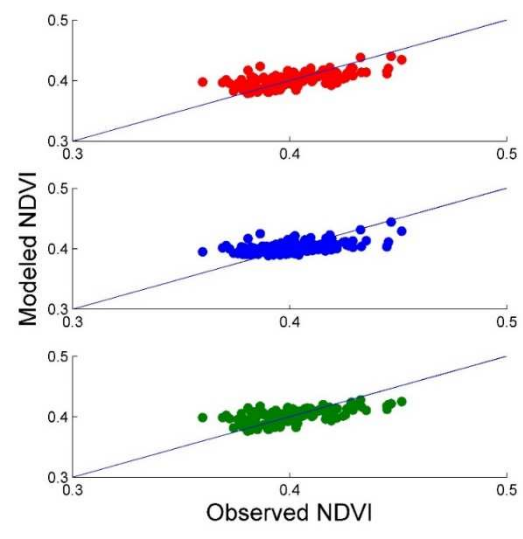
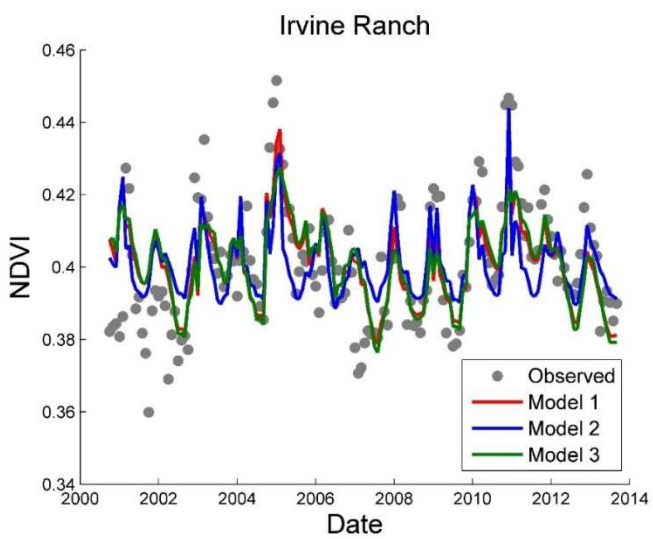


Figure A.8. Irvine Ranch Water District Model Results

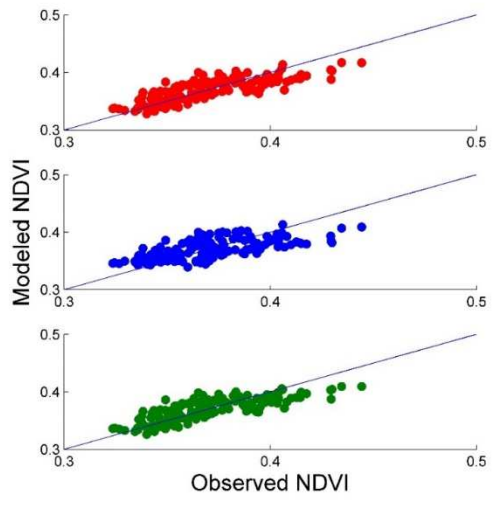
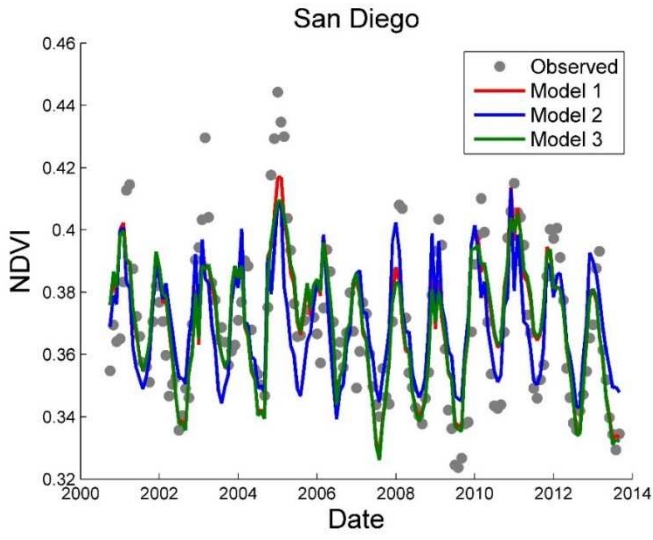


Figure A.9. San Diego Model Results