Examining the relationship between ozone and sulfur dioxide concentrations, urbanization, and plant vigor in the Sonoran Desert, Arizona, 1992-2011

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Abstract

The saguaro cactus is an iconic symbol for the American Southwest but has experienced population declines over the last 75 years. The cause of this decline is unknown. This project used remotely sensed data to assess the impact of urbanization and air pollution on plant health in the Sonoran Desert of Arizona for the years 1992 to 2011. Yearly averages of ozone and SO_2 measurements were graphically compared to urbanization from NLCD images and plant vigor from MSAVI2 images. A linear regression was conducted to analyze the relationship between each variable. Ozone concentration did not correlate with plant vigor. SO_2 concentration negatively impacted plant vigor. The results of the project could indicate if sampling saguaro cactus tissue for ozone and SO_2 concentrations should be considered in future research and how urban planning can affect the cactus health in preserve areas.

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Introduction

The Sonoran Desert is one of the most biologically diverse ecosystems in North America. The Desert is the home of over 500 vertebrate species and 2,000 plant species (CBD 2015) including several iconic species, such as the Gila monster (*Heloderma suspectum*) and the saguaro cactus (*Carnegiea gigantean*). The saguaro cactus can grow to over 12 m tall (NPS 2015a) and weigh over ten tons (Kolberg and Lajtha 1997). The saguaro cactus is slow growing and can live for over 150 years (Kolberg and Lajtha 1997). Saguaro cactus play a critical role in the Sonoran Desert ecosystem by providing food and shelter for numerous animals, including humans.

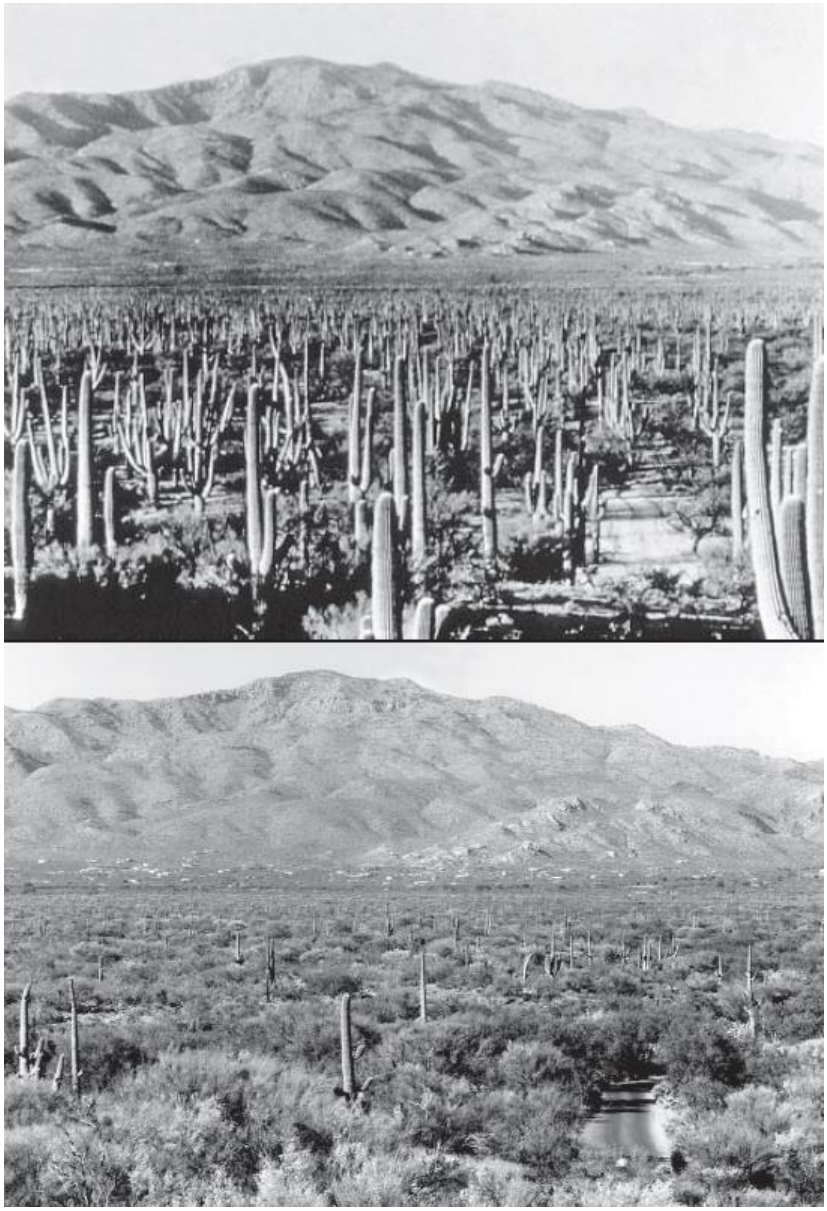

Figure 1. Saguaro cactus forest in SNP 1935 (top) and 1998 (bottom). Saguaro cactus populations have been declining the cause of which is not yet known. Image modified from Ahnmark and Swann, 2009.

Cactus provided a source of wood for fires during early periods of settlement in Arizona. The saguaro cactus population declined in the early 1900s as cities such as Tucson and agriculture and mining industries expanded

(Ahnmark and Swann 2009). Saguaro National Monument, now Saguaro National Park (SNP), was established in 1933 to help preserve the species and others unique to the area (Ahnmark and Swann 2009). Population density of saguaro cactus in SNP has been declining since the 1940s despite efforts preserve the dense stands(Kolberg and Lajtha 1997; Ahnmark and Swann 2009) (Figure 1).

Declines in the saguaro cactus population have been attributed to changing climate, a mysterious browning on cactus tissue, air pollution, and habitat loss (Kolberg and Lajtha 1997). The Sonoran Desert is among the fastest urbanizing areas in the United States. Urbanization directly transforms landscapes by affecting biodiversity, ecosystem productivity, watershed discharge characteristics, and biogeochemical cycling (Alberti 2005; Shen et al. 2008). Urban areas are sources of greenhouse gases, air pollutants, and heat. Saguaro cactus are particularly vulnerable to air pollution given their longevity and inability to remove toxin-affected tissue (Kolberg and Lajtha 1997).

Purpose and scope

This project will examine if a relationship between the urbanization of Arizona, ozone and SO_2 concentrations, and the decline of saguaro cactus in the state can be observed using remotely sensed data. Urban expansion resulting in habitat loss will not be directly examined. The project will examine data from the years 1992 to 2011.

The saguaro cactus is a nationally recognized symbol of the American Southwest. It has been incorporated into product labels and Western films despite the cactus having a much more limited range. The saguaro cactus and the preserves designed to protect Sonoran Desert ecosystems are major tourist attractions with SNP receiving over 6.5 million visitors in the last decade (NPS 2015b).

Study area

The Sonoran Desert covers over 3,000,000 km^2, extending from northwestern Mexico into southeastern California and central Arizona (CBD 2015). The Desert has a harsh environment with a mean maximum air temperature greater than 30 °C and less than 200 mm of precipitation each year (Keys et al. 2007; Esbah et al. 2009; Buyantuyev and Wu 2012). The Desert is part of the Basin-and-Range Province (Buyantuyev et al. 2010); the relatively flat alluvial plains are surrounded by isolated mountain ranges.

The City of Phoenix started as an agricultural community after the Civil War, making use of irrigation channels dug by the Hohokam centuries earlier (Roach et al. 2008; Esbah et al. 2009). Urbanization of Phoenix and the surrounding area increased after the invention of air conditioning in the 1950s (Esbah et al. 2009). The resident population increased 70% from 1980 to 2000 (Keys et al. 2007). Today, the Phoenix Metropolitan Area is comprised of more than twenty cities (Keys et al. 2007; Esbah et al. 2009; Buyantuyev et al. 2010; Buyantuyev and Wu 2012; Shrestha et al. 2012) and contains more than four million people (Buyantuyev and Wu 2012). Much of the urban growth occurred as low-density residential housing at the expense of open desert and agricultural lands (Keys et al. 2007; Buyantuyev et al. 2010; Shrestha et al. 2012). The Phoenix Metropolitan Area was designed with automobiles in mind (Keys et al. 2007; Roach et al. 2008; Shrestha et al. 2012). The automobile remains the dominant mode of transportation for residents with only 2.3% of workers regularly using public transportation to commute (Shrestha et al. 2012).

Data and methods

Ozone and SO_2 measurements from the EPA's AirData dataset (2015) for the years 1992, 2001, 2006, and 2011 were used to estimate the concentrations of these pollutants at monitor site locations. The daily measurements for 8 hour maximum concentrations were averaged to create mean annual values of each pollutant for each year. Monitor locations were mapped in ArcGIS using the provided coordinates (Figure 2). Each monitor site

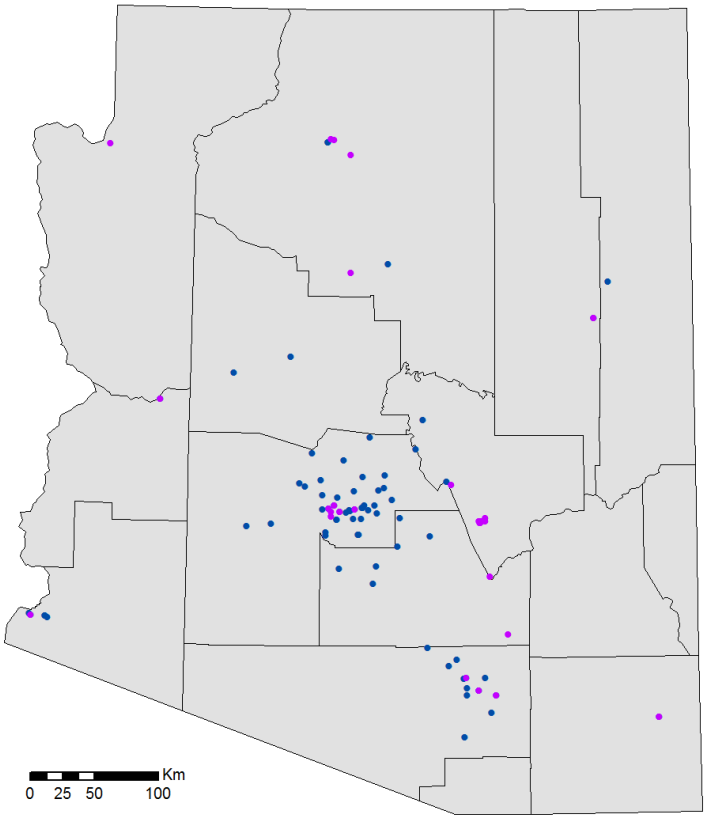

Figure 2. Location of ozone (blue dots) and SO_2 (purple dots) monitor sites in Arizona. County boundaries represented by black lines. Monitor location data from EPA AirData, 2015.

location was buffered by the maximum value in the measurement scale range. Monitor sites with range scales listed as “50km to hundreds of km” were given a buffer of 100 km.

Urbanization was examined within each monitor site buffer using data from the National Land Cover Database (NLCD) for the years 2001, 2006, and 2011. The NLCD 1992/2001 Retrofit Land Cover Change Product was used for the year 1992. The NLCD images have been shown to correctly identify low intensity development with 80% accuracy and open space/very low intensity development with 66% accuracy in Maricopa County (Shrestha et al. 2012), which contains Phoenix. These data were reclassified using Anderson Level I classifications (Anderson 1976). The area and proportion of each land cover class was calculated for each monitor site buffer for each year.

Vegetation vigor was assessed using a vegetation index. The normalized difference vegetation index (NDVI) has been used to assess the phenological response to urbanization in the Phoenix Metropolitan Area (Buyantuyev et al. 2010; Buyantuyev and Wu 2012). A common issue with using vegetation indices in desert or barren environments is reflectivity from soil surfaces; a vegetation index which accounts for this source of reflectivity such as the revised modified soil-adjusted vegetation index (MSAVI2) might yield more accurate results (Lillesand et al. 2008). MSAVI2 values were calculated from the Landsat 4-5 TM dataset. Landsat data were used to create the NLCD so both datasets have a resolution of 30 m. Landsat images with less than 20% cloud cover were selected as close to October 31 as possible for the years 1992, 2001, 2006, and 2011. Late October was chosen to reduce the impact of spring and fall rains after which perennials and annuals experience dramatic growth in the Desert (Buyantuyev and Wu 2012). The minimum, maximum, mean, standard deviation, and median MSAVI2 values were calculated for each monitor site buffer for each year.

The air pollutant concentrations and the median MSAVI values near air pollution monitor sites that were operating for all years during the study period were graphed for comparison. Linear regression analysis was run on median MSAVI2 values, the proportion of urban area within the monitor site buffers, and the pollutant concentrations using Microsoft Excel 2013.

Results and discussion

Urbanization increased from approximately 17% from 5,600 km^2 to 6,900 km^2 from 1992 to 2011. The overall proportion of urban area remains at less than 0.025 of the total area (Figure 3).

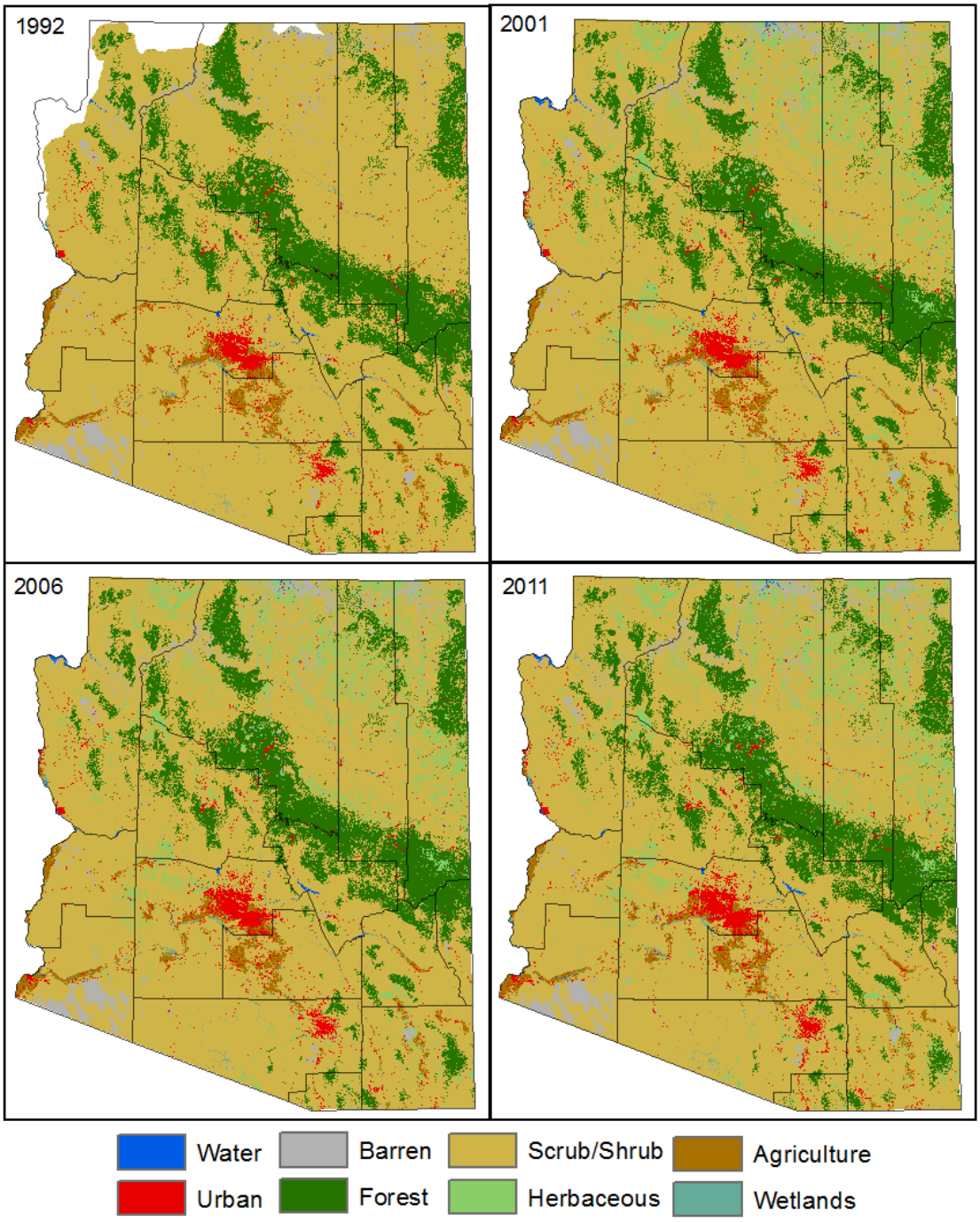

Figure 3. Reclassified land cover images for the for the chosen study period. Urban areas increased approximately 1% per year but remains a minor land cover class concentrated primarily near Phoenix and Tucson.

MSAVI2 values throughout the state ranged from 629 to 3554 with higher values indicating more vigorous plant growth (Figure 4). The ranges were the same for areas within the monitor site buffers. Mean values were typically near 1200 with a standard deviation of 450. Median values were moderately lower than the mean and typically fell within 900 to 1100.

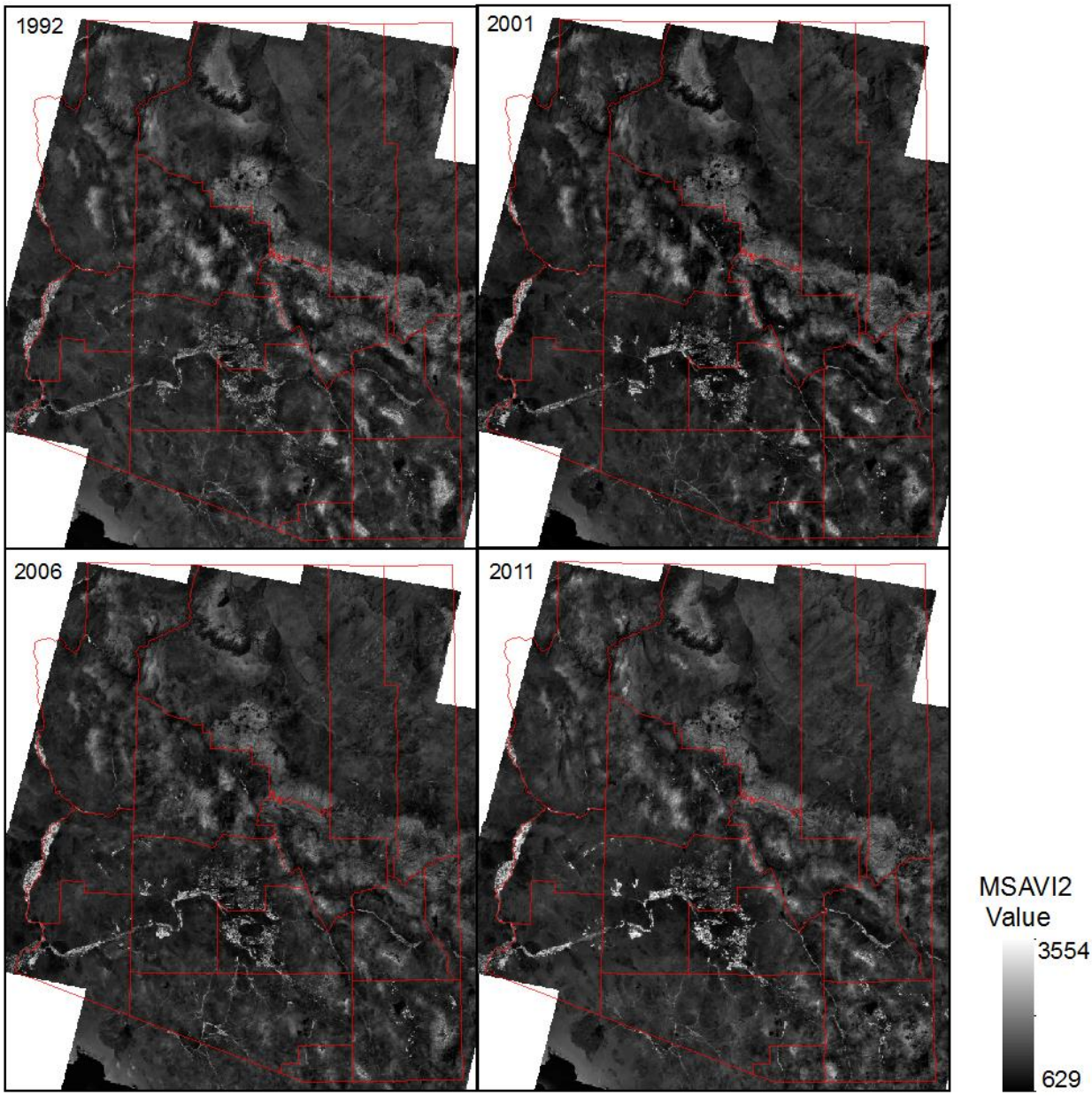

Figure 4. MSAVI2 images were mosaicked to cover most of the state. The descriptive statistics of the values across the state did not vary considerably between years.

Four ozone monitors operated each year during the study period. These monitors are located near Tucson, Arizona, and a variety of coverage areas and proportions of urban land cover (Table 1). Ozone concentrations at these sites appear to have little to no correlation to the MSAVI2 median values for the surrounding areas (Figure 5). No sulfur monitors operated throughout the entire study period.

Table 1. Statistics for four ozone monitor sites and the state of Arizona.

		Proportion of urban cover			
Monitor Site ID	Area (km^2)	1992	2001	2006	2011
40190021	50	0.108	0.126	0.140	0.144
40191011	50	0.907	0.917	0.924	0.925
40191018	7498	0.063	0.073	0.078	0.081
40191020	4728	0.015	0.020	0.022	0.022
Arizona	294000	0.019	0.021	0.022	0.024

The linear regression analysis confirms this apparent lack of correlation. The adjusted R^2 value for median MSAVI2 values (dependent variable) and ozone concentrations (independent variable) was 0.015; urban proportion had a much higher adjusted R^2 value at 0.133. The regression analysis also revealed urban proportion only explains a fraction of the

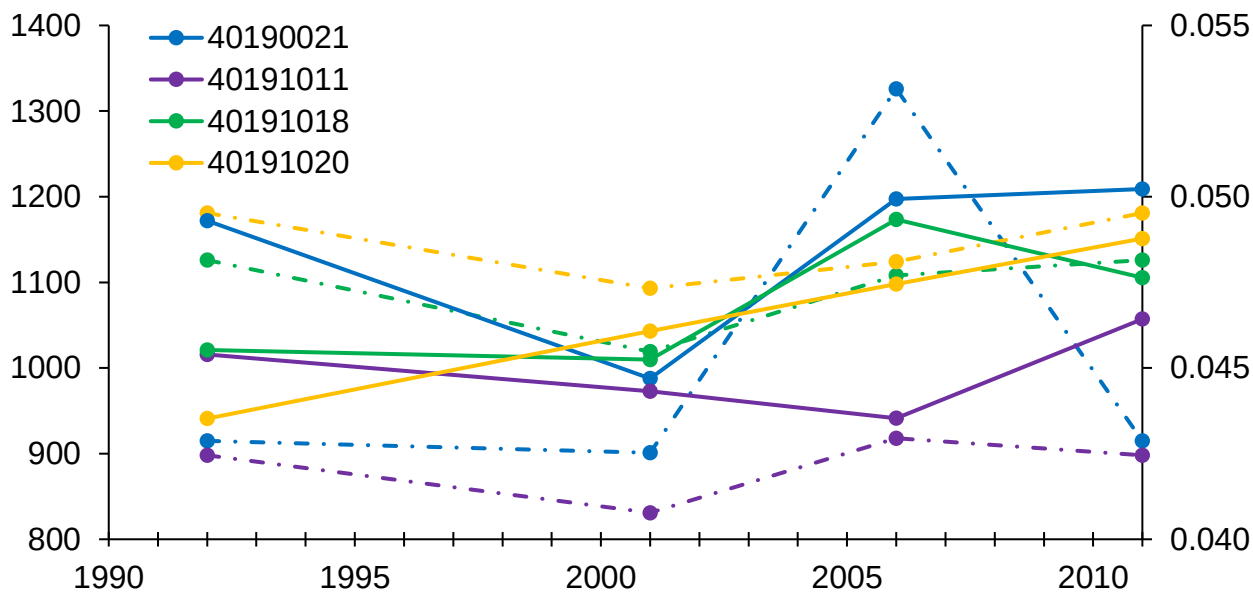

Figure 5. Median MSAVI2 values (left axis, dashed lines) and ozone concentrations in ppm (right axis, solid line) show no observable correlation. Some increases in both values coincide, such as at monitor 40190021 from 2001 to 2006, while other show a negative correlation.

variation in ozone concentrations (adjusted R^2=0.248). Ozone has been shown to cause necrosis in flowering plants concentrations (USDA 2012), as such, ozone and plant vigor were expected to correlate negatively. However, ozone concentration are not

explained primarily by urban proportion so other factors, such as miles driven by tourist and freight trucks, should be included in the analysis. SO_2 however did show a minor negative correlation to MSAVI2 values with an adjusted R^2 value of -0.053. SO_2 in the air reacts with water to form HSO_3^{1-} and SO_3^{2-} which have been shown to cause necrosis in plants (Brychkova et al. 2007) and was expected to negatively impact MSAVI2 values. Urban proportion is a major factor for modeling SO_2 concentrations (adjusted R^2=0.634).

Summary

The Sonoran Desert is biologically diverse ecosystem which contains important species such as the saguaro cactus. The saguaro cactus has experienced a decline in population. Air pollution has been proposed as a possible cause for the decline. This study found ozone concentrations did not impact plant vigor as assessed by MSAVI2 values. Additionally, ozone concentrations are not well modeled by the proportion of urban land cover. SO_2 was found to have a slight negative impact on overall plant vigor and was modeled well by the proportion of urban land cover.

These results support a recent view in the literature (Ahnmark and Swann 2009) that other factors such as number of days with freezing temperatures and livestock grazing have a greater impact on plant health in the Sonoran Desert. A future study incorporating these factors as well as rainfall conditions might better model plant health in the region.

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