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Using remote sensing approach to analyze vegetation response to drought and landscape changes in arid regions

Xu Qiang

Faculty of Forestry, University of British Columbia, 2424 Main Mall, Vancouver, BC, V6T1Z4, Canada

qiangx01@student.ubc.ca

Abstract. Arid regions, characterized by low annual precipitation, unique vegetation, and distinctive hydrological cycles, play a significant role in maintaining ecological balance. However, these regions, with their hostile and remote environments, present unique challenges for field research. This study utilizes remote sensing technology, particularly the Normalized Difference Vegetation Index (NDVI), to evaluate the ecosystem's response to drought and understand the relationship between vegetation variability and other landscape features including elevation, soil type, and changes in land use or land cover. Six sites within the city, each of 100 square kilometers and representing diverse landscapes, were selected for the study. Key datasets describing land features were collected from official and authentic websites. A series of ArcGIS-based data processing methods were applied to discern patterns in the relationship between landscape features and vegetation variability, with a particular focus on periods of wet and dry years. The wet and dry years are identified as 2005 and 2009 respectively, based on average rainfall data. Notably, NDVI values in the wet year are consistently higher than in the dry year, with the greatest differences observed in undeveloped or shrubland areas (sites 3, 5, and 6). In terms of land cover, urban development increases in sites 1, 2, and 4 between 2004 and 2008, while shrubland decreases in sites 3, 5, and 6. This development corresponds to a contraction of vegetation cover. The study areas are primarily characterized by loamy soils, with variations in clay and sand composition. These findings underscore the impacts of rainfall and urban development on vegetation health in arid regions.

Keywords: arid region, remote sensing, NDVI, vegetation variation.

1. Introduction

Vegetation is a general term for plants community on the ground surface, including forests, shrubs and grassland, and it plays important role in hydrological cycle, energy exchange and preventing desertification and maintain soil and water in arid and semi-arid regions [1,2]. Arid vegetation cover is typically found in regions with extremely low annual precipitation, which is normally less than 250mm (10 inches) per year. These areas have distinct vegetation characteristic. Arid vegetation tends to be sparse and contain unique species such as Saguaro cactus, Creosote bush and Ponderosa pine. These arid plants are highly drought-tolerant with specific adaptions, such as deep roots, reduced leaves, succulence, slow growth rates, and strategies to store water, all of which help them survive in the harsh conditions [3-5].

The hydrologic cycle in arid climate region is different from other climates and can be briefly attributed to low precipitation, high evapotranspiration, and low water availability [3]. Arid regions receive significantly less precipitation compared to more humid climates, which greatly impacts the hydrologic cycle. This results in reduced surface runoff, soil moisture, and groundwater recharge. Due to high temperatures and low humidity, evaporation rates are much higher in arid areas. This leads to rapid water loss from soil and water bodies, further contributing to the dry conditions. The hydrological processes and energy exchange are illustrated in Figure 1. Due to the water scarcity, spatial and temporal pattern of vegetation cover are strongly affected by precipitation and are highly sensitive to climate variability. Understanding the relationships between reduced rainfall, land use change and vegetation cover is essential for drought assessment and water resources management.

Since the arid regions-deserts are generally remote, inaccessible, and inhospitable [6] and with limited water resources, physical field work is demanding and dangerous for researchers. The low-density of vegetation and slow growth rates can also make it challenging to collect sufficient and long-term data [7]. However, remote sensing can provide a novel technology to obtain more informative data with long-term monitoring of land cover change and vegetation variation. Therefore, Normalized Difference Vegetation Index (NDVI) product, which depicts vegetation greenness, has become a more reliable source to evaluate arid ecosystem condition.

The purpose of this study is to understand the respond of vegetation to drought condition or reduced rainfall and explore the relationship between vegetation variability and other landscape features including elevation, soil type, and land use/land cover (LULC) change by utilizing a variety of remote sensing data with the most important one-NDVI.

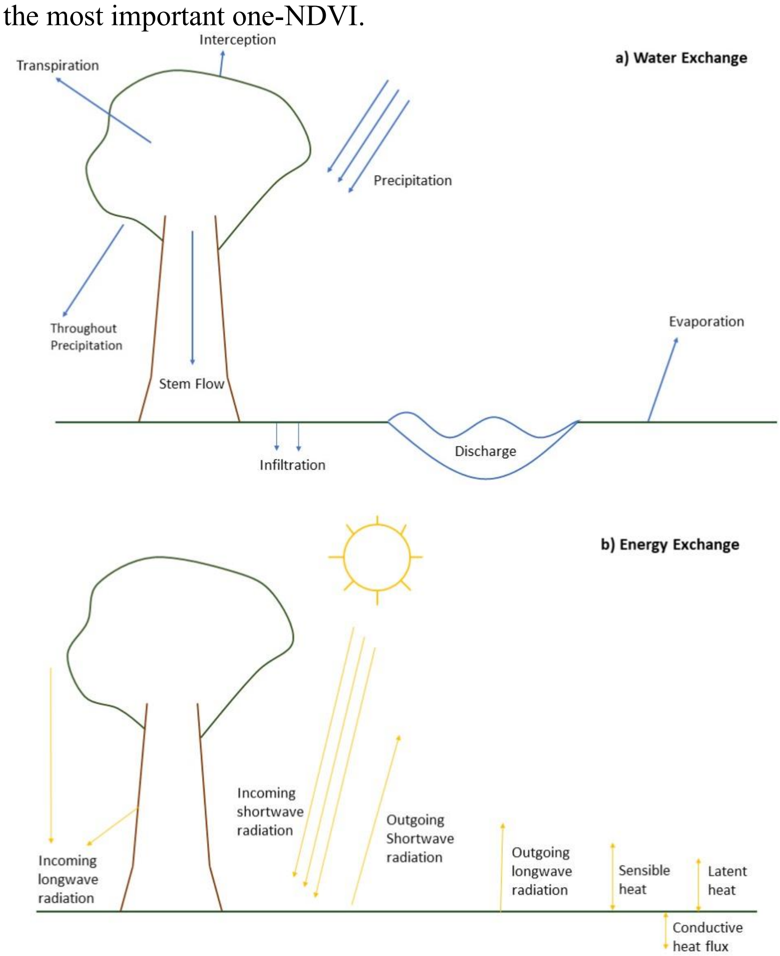

Figure 1. Conceptual diagram of hydrological cycle and energy balance describing water and energy exchange between land surface, vegetation, and rainfall.

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2. Methodology

2.1. Site selection

Phoenix, Arizona is a large city in the southwestern U.S. and has the fifth largest population. Located in the northeast of Sonoran Desert, Phoenix' climate is classified as hot desert (BWh) according to Köppen climate classification [8]. Six study sites are selected within the boundary of Phoenix, which was an arid region. These six sites are almost distributed evenly throughout the city of phoenix and contain multiple landscapes (Figure 6). Each site was 10 km by 10km. Sites 1, 2 and 4 are developed urban areas with lower elevation, while sites 3, 5, 6 are shrub lands with higher elevation (Table 1).

2.2. Data collection

In order to determine the wet year and dry year for the study area, precipitation data from 2002 to 2021 are downloaded from the Arizona Meteorological Network (AZMET) website, which provides meteorological data and weather-based information in southern and central Arizona by using a network of automated weather stations located in both rural and urban production settings [9]. The Phoenix Greenway and Phoenix Encanto are the only two active stations in the city of phoenix, and their locations are indicated in Figure 2.

Provided by NASA and USGS, Application for Extracting and Exploring Analysis Ready Samples (AρρEEARS) was a platform where offered a simple and efficient way to access and transform geospatial data from a variety of MODIS data, which enabled to extract and download the NDVI data for study areas in the summers of dry year and wet year. The NDVI data is extracted from MOD13A1-Terra Vegetation Indices 16-Day L3 Global 500 m SIN Grid which has a spatial resolution of 500m and a temporal resolution of 16 days [10].

Elevation raster data of the study area is retrieved from National Elevation Dataset (NED) released by National Atlas of the United States. The elevation data showed the terrain at a resolution of 100 meters. The NED was a raster product assembled by the U.S. Geological Survey, designed to provide national elevation data in a seamless form with a consistent datum, elevation unit, and projection. The data we used were edited by National Atlas of the United States [11].

Soil type data covering over a century were collected from Soil Survey Geographic Database (SSURGO) served by U.S. Department of Agriculture-Natural Resources Conservation Services (USDA-NRCS). The data were gathered through field surveys throughout most areas of U.S., and soil samples were analyzed in laboratories [12].

Land cover type data for wet year and dry year were collected from National Land Cover Database (NLCD) product served by Multi-Resolution Land Characteristics Consortium (MRLC), which could offer more comprehensive delineation of shrub and grass classes for the study area. The NLCD provided nationwide data on land cover and land cover change at a 30m resolution with a 16-class legend based on a modified Anderson Level II classification system [13].

2.3. Data processing

The raw precipitation dataset from 2002 to 2004 for two stations recorded daily and monthly rainfall volume. The monthly precipitation data were added up to obtain the annual precipitation for each year for the two stations. The average annual precipitation of two stations was used to represent the precipitation of the study areas. Among the 20-year period, the year with highest precipitation would be determined as the wet year, while the one with lowest would be determined as the dry year.

The shapefile of study areas was first uploaded, and the data for interested areas were downloaded in GeoTiff format, which could be directly processed in ArcGIS. The NDVI data for the whole Phoenix area were selected from the MOD13A1 product with 14 layers in total that represented summer periods for the wet and dry year. Then, after using 'extract by mask' tool to extract the six target sites, I 'used zonal statistic' tool in ArcGIS to conduct a spatial analysis for the six sites. Mean NDVI values and standard deviations within each site were derived from this analysis.

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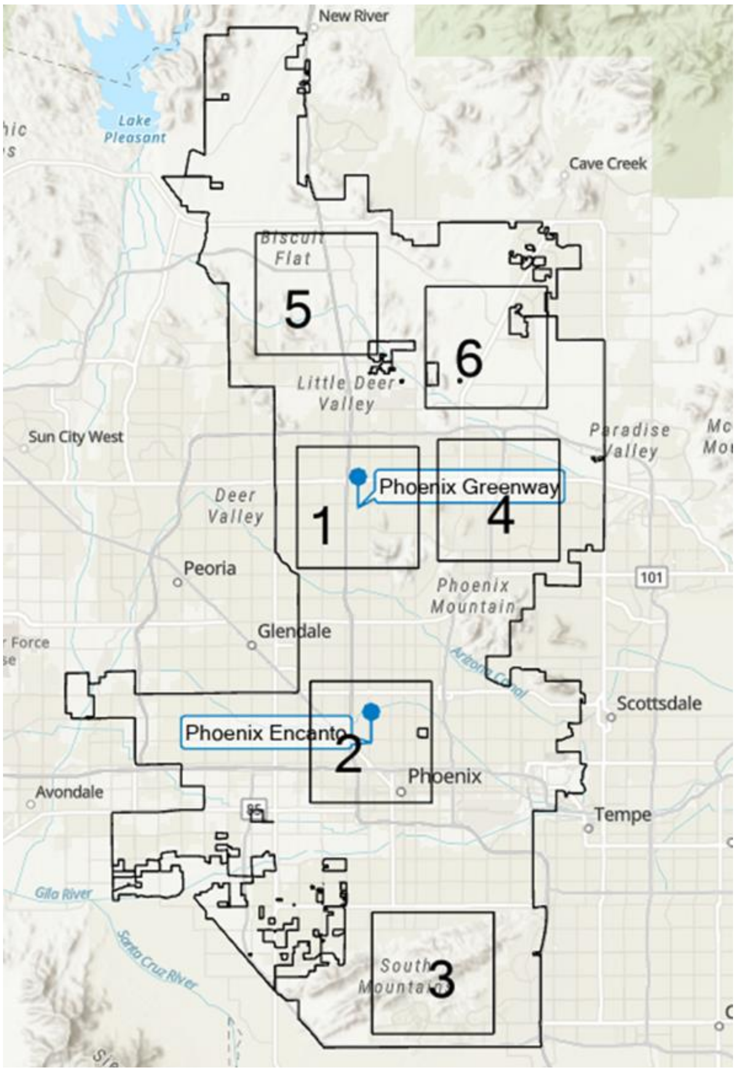

Figure 2. A schematic diagram of the locations of study sites and rain gauges, where the black numbers represent the sites names, and the blue pins represent the rain gauges.

Both elevation data and land cover type data were raster data, so they undergone 'extract by mask' too to obtain the discrete zonal data for six sites. By using the resolution, the area of a single raster cell could be calculated, and the area of a certain land cover type could be then calculated by multiplying the cell area and the number of the cells. According to this information, I determined the major land cover type for each site and its specific area. Since the soil data were vector data, I used 'clip' tool to extract target sites and 'dissolve' tool to attribute the discrete lands with the same soil type into one single feature, thus determining major soil types for each site based on the area of which a certain type of soil taken up.

3. Results

The average of rainfall datasets of two rain gauges were used to represent the annual rainfall volume for entire Phoenix. The range of its annual precipitation were around 4 inches to 11 inches, and there was a rough precipitation pattern: in the period of 2002 to 2021, the annual precipitation increased to a peak and then decreased in every 3-4 years. During this period, the highest annual precipitation was about 11 inches in 2005, which was determined as the wet year, while the lowest annual precipitation was about 4 inches in 2009, which was determined as the dry year.

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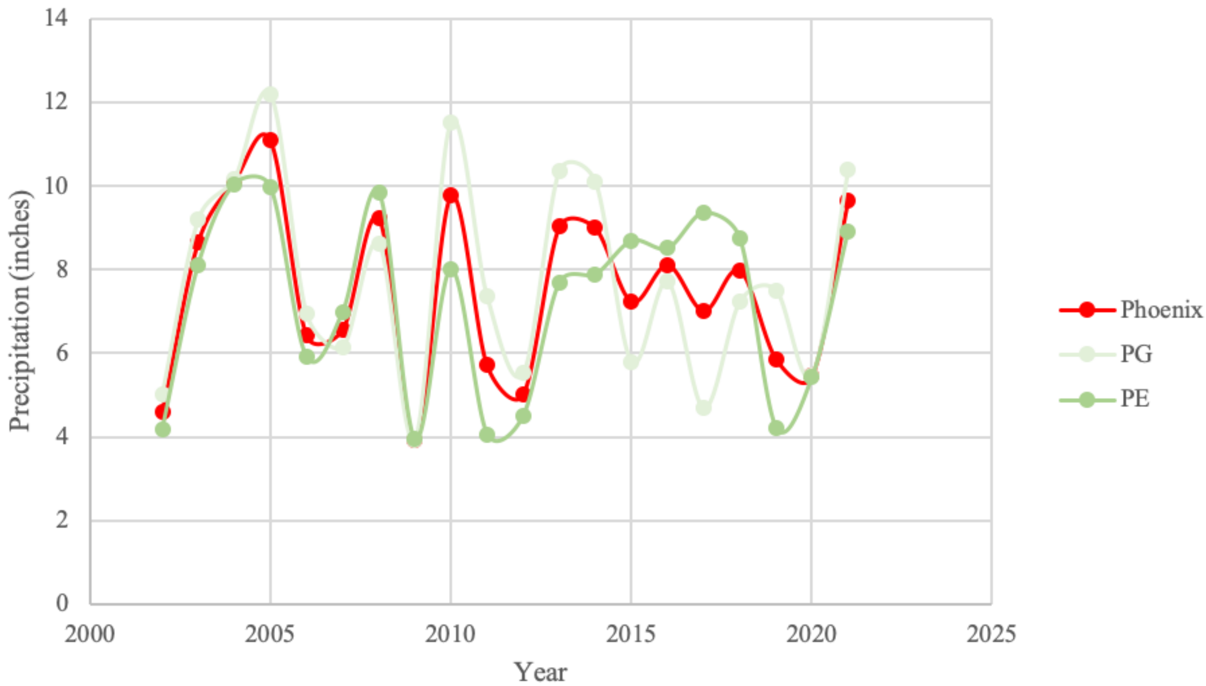

Figure 3. Annual precipitation graph for Phoenix from 2005 to 2009, where PG represents Phoenix Greenway, PE represents Phoenix Encanto, and Phoenix represents the mean annual rainfall between the two rain gages.

For each site, overall NDVI values in 2005 (wet year) are higher than that in 2009 (dry year). For each site, the NDVI values basically keep steady with slight fluctuation throughout the whole summer period. In 2005, all NDVI values are around 0.2 across 6 sites during the summer period. In 2009, most of NDVI values throughout the summer are lower than 0.2. The mean values of NDVI of 6 sites in 2005 are respectively 0.22, 0.20, 0.20, 0.20, 0.21, while the mean values of NDVI of 6 sites in 2009 are respectively 0.20, 0.19, 0.16, 0.19, 0.15, 0.17. NDVI values in sites 3, 5 and 6 decrease by around 0.5, which shows significant temporal differences, while the NDVI differences in site 1, 2, 4 are only 0.1 or 0.2, which are much smaller compared with site 3, 5 and 6 To be noticed, the standard deviation of NDVI in site 2 is larger than others, which means there is obvious variation across site 2 in either wet or dry year.

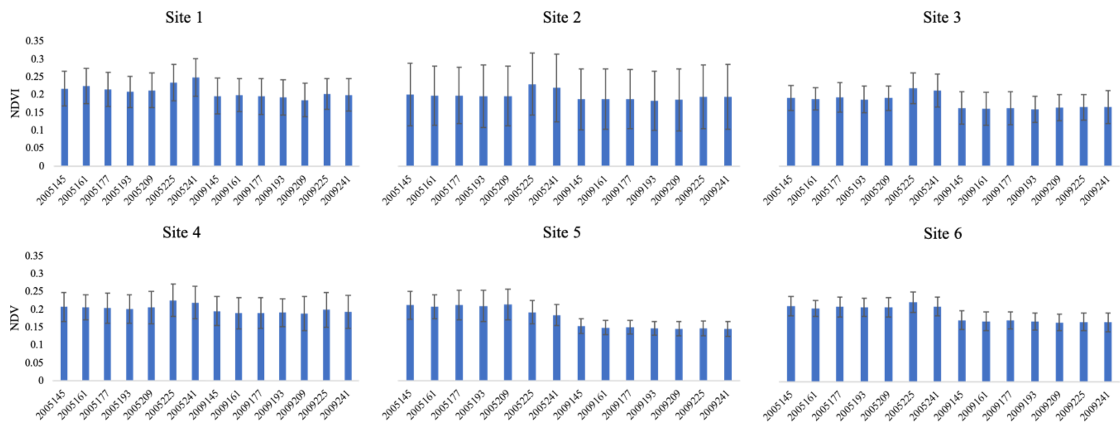

Figure 4. Changes in NDVI values for each site in summer of 2005 and 2009.

Sites 1,2,4 can be categorized as developed urban areas. The major land cover type of these 3 sites in 2004 and 2008 are constantly developed areas. Site 1 has a mean elevation of 409.87 m. Site 2 has a

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mean elevation of 336.63 m with the lowest standard deviation of 7.12m. Site 4 has a mean elevation of 444.93 m. Since site 1 has a flat plain, it is intuitive that the majority of this area is used for urban development as indicated by 2004 & 2008 Land Cover map (Figure 6). Similarly, site 2 and site 4 have low variation in elevation, which is suitable for urban development as well. However, as site 1 has the least developed high-density urban area among these 3 sites, the NDVI value of site 1 is larger than its counterparts- site 2 and site 4.

Sites 3, 5, 6 can be categorized as undeveloped or shrubland. The major land cover type of these 3 sites in 2004 and 2008 are constantly shrub/scrubland. Site 3 has a mean elevation of 480.21 m, but it has the highest elevation 810 m with the highest standard deviation of 108.79m. Site 5 has a mean elevation of 479.19 m. Site 6 has a mean elevation of 513.83 m. According to 2004 &2008 Land Cover data (Figure 6), shrubland/scrubland takes up a large portion of site 3, 5, 6.

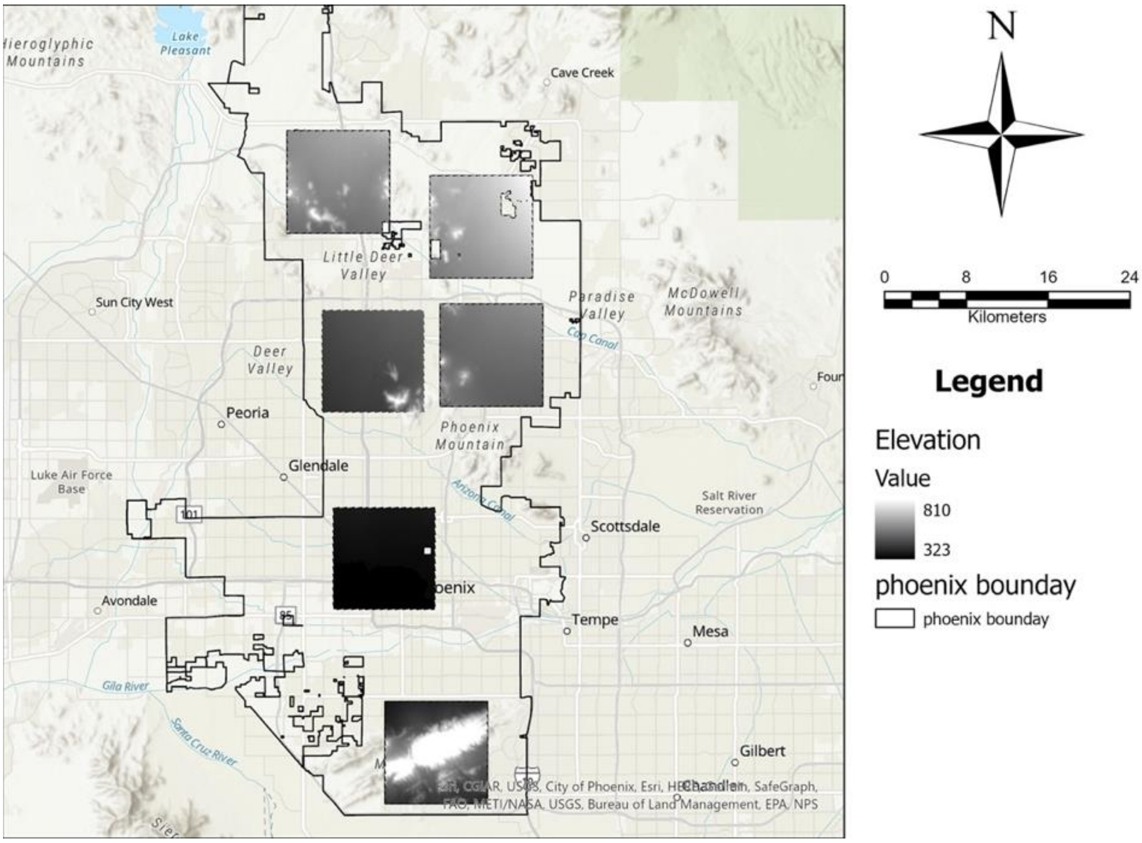

Figure 5. Elevation map.

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Table 1. Data of elevation, land cover types and soil types for 6 sites.

	Mean Elevation (m)	Major Land Cover Type	Change in Area from 2004 to 2008 (km^2)	Major Soil Types	Area (km^2)	Total Soil Area (km^2)
Site 1	409.87	Developed urban area	1.27	Gilman loam, 0 to 1 percent slopes	17.69	54.55
				Mohall clay loam	15.66	
				Mohall loam MLRA 40	11.43	
				Laveen loam, 0 to 1 percent slopes	9.77	
Site 2	336.63	Developed urban area	0.23	Mohall clay loam	26.68	64.29
				Glenbar clay loam, 0 to 2 percent slopes	20.98	
				Gilman loam, 0 to 1 percent slopes	16.63	
Site 3	480.23	Shrub/scrub	-2.64	Rock land	30.54	54.93
				Rock outcrop-Cherioni complex	24.39	
Site 4	444.93	Developed urban area	1.37	Gilman loam	39.31	61.81
				Estrella loam	22.5	
Site 5	479.19	Shrub/scrub	-13.02	Carefree cobbly clay loam, 1 to 8 percent slopes	42.69	60.41
				Ebon very gravelly loam, 1 to 8 percent slopes	9.5	
				Cherioni-Rock outcrop complex, 5 to 60 percent slopes	8.22	
Site 6	513.83	Shrub/scrub	-6.39	Momoli gravelly sandy loam, 1 to 5 percent slopes	30.7	56.15
				Pinamt-Tremant complex, 1 to 10 percent slopes	8.76	
				Gilman loam	8.42	
				Tremant-Rillito complex	8.27	

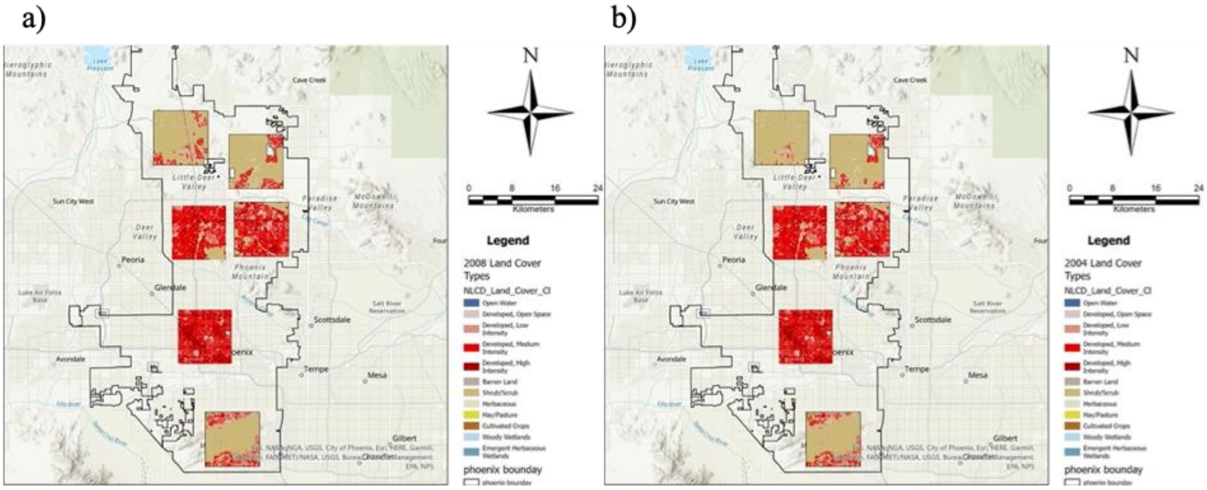

Figure 6. Land cover map with a) showing the land cover distribution of 2004 and b) showing that of 2008.

From 2004 to 2008, which represents the target period between 2005 to 2009, the developed urban area in site 1,2,4 had respectively increased by 1.27, 0.23, and 1.37 km^2, while the shrub/scrubland in site 3,5,6 had decreased by 2.64, 13.02, and 6.34 km^2. The changes in shrubland areas for site 3,5,6 were much larger than the changes in developed urban areas for site 1,2,4. The decreases in shrubland were mainly caused by the expansion of developed area, so overall for all sites the developed urban area were expanding, while the vegetation were shrinking.

According to Table 1, most soil of study areas were loamy, although there were varieties such as clay loam or sandy loam (Cherioni complex), and rock land or rock outcrop. Loamy soils are the mixture of sand, silt, and clay particles exhibiting their properties separately. Sand has low water-holding capacity, good aeration and high drainage rate; silt has medium water-holding capacity, medium aeration and medium drainage rate; clay has high water-holding capacity, poor aeration and very slow drainage rate [14]. The properties of loamy soil with high clay content tends to be dominated by clay, while the one with high sand content tends to be dominated by sand. Except for site 3 where the surface there was composed of rocks, the soils in site 1,2,4,5,6 were mainly loamy, which took up more than half of the total area.

4. Discussion

These results described above reveal strong relationship between NDVI patterns and precipitation, elevation, land cover, soil, and vegetation type. For example, the variation of NDVI in site 2 may be the result of majority urban area. Another example is site 3, which is located in the mountainous area. As site 3 is in a high elevation area, the vegetation may be sparse. Therefore, the NDVI values are relatively low.

The NDVI pattern shows strong correlation with the precipitation pattern. As the precipitation decreased from 2005 to 2009, the NDVI values showed similar trend.

Another important factor affecting NDVI is the land cover. From 2004 to 2008 (2005-2009), developed urban areas expand a lot and intrude into sites 3,5,6 where there were not as much urban areas in 2004. Some low-density and mid-density developed areas in sites 124 transform into high-density developed urban areas. The overall precipitation volume in 2005 is much higher than that in 2009 (Figure 3). Thus, reasonably, the NDVI values of all 6 sites in 2004 is higher than that in 2008. To be noticed, the NDVI values of site 3, 5, 6 otherwise results from the combination of the decrease in precipitation and the increase in urban developed area. Affected by the land cover factor and precipitation factor, the vegetation decreases, and thus NDVI decreases. The NDVI values of site 356 are lower than that of site 124 because of the presence of herbaceous land in site 124, which has greatly increased the NDVI value. Although site 356 are full of shrub/scrubland with vegetation, herbaceous land has much larger NDVI value and has greater ability to affect the NDVI value than shrub/scrub land. Even a small area of herbaceous can increase the NDVI value of a whole site as shown by Figure 4 & 6.

Lastly, the land surface characteristics including elevation and soil also play a role. In general, the elevations of site 124 are lower than that of site 356 (Figure 5 & Table 1), which is also a reason for urban development in 124. In the lower elevation area (i.e., site 124), the common vegetation is composed of Saguaro cactus (tree-like tallest cactus in US, native to Sonoran Desert), Creosote bush (shrub with fragrant evergreen leaves and yellow flowers, well adapted to dessert, native species), and Palo Verde (small deciduous tree with green bark and yellow flowers. Well adapted. Native), which are greenery vegetation that can lead to higher NDVI. In the higher elevation area (i.e., site 356), Ponderosa Pine (large evergreen coniferous tree (cones and needles, hardy species, wide tolerance) and Manzanita (small evergreen shrub or trees with twisting branches, orange or red bark, glossy leaves, and clusters of pink/white flowers) make up the main vegetation, resulting in shrub/scrub land, which leads to lower NDVI. The reason why Site 3 has the lowest NDVI value may be due to its soil type being rock. Rocks are unsuitable for plant growth, so there would be less vegetation in this area, thus leading to a smaller NDVI value. This is also why the increasing area for urban development was the lowest among site3,5,6. As the soil types of other sites were the same loamy texture, the soil may not have larger impact than other factors discussed above on the NDVI values for each site.

5. Conclusion

In this study, I investigated the vegetation response to drought conditions and the relationship between vegetation variability and landscape features, specifically focusing on arid regions around Phoenix, Arizona. Using remote sensing data and NDVI as a primary indicator, we analyzed how vegetation in arid ecosystems reacts to climatic and human-influenced changes.

This study reinforces the importance of considering a range of factors when interpreting NDVI data and assessing vegetation health in arid regions, offering invaluable insights for water resources management and drought assessment. While precipitation is a key driver of vegetation patterns, the interactions between precipitation, land use, elevation, soil type, and plant species make for a complex system where changes in one factor can have significant implications for the others.

Further research could explore how these factors interact over different time scales and under different climate change scenarios including other factors such as temperature. This would help us better predict how arid ecosystems might respond to future changes and provide a more holistic understanding of the vegetation variation in arid regions, thereby managing these valuable and sensitive environments.

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