Potential Emergence of Dengue in the Phoenix Metropolitan Area:

A Micro-climatic and Demographic Analysis

by

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ABSTRACT

The spread of dengue worldwide currently places half of the world's population at risk. In the absence of a dengue vaccine, control of the disease requires control of the mosquito species that transmit the virus. The most important of these is. Advances in research detailing the responsiveness of *Aedes aegypti* to small changes in climate enable the production of more sophisticated remote sensing and surveillance techniques for monitoring these populations. Close monitoring of global dengue activity and outbreaks likewise enables a greater specificity when determining to which human populations the virus is most likely to spread.

There have been no locally acquired cases in Arizona to date, but the high abundance of *Aedes aegypti* in the Phoenix Metropolitan area raises concern within the Arizona Department of Health Services over the potential transmission of dengue in the city. This study develops a model that combines mosquito abundance, micro-climatic and demographic information to delineate regions in Phoenix that are most support transmission of dengue. The first chapter focuses on the impact that daytime high and low temperatures have on *Aedes aegypti's* ability to become infectious with dengue. It argues that NDVI (normal difference vegetative index) imaging of the Phoenix area can be used to plot areas where mosquitoes are most likely to become competent vectors. The second chapter focuses on the areas in the city where mosquitoes are most likely to be exposed to the virus. Based on proximity to Phoenix and the high volume of traffic across the Arizona-Mexico border, I treat the Mexican state of Sonora as the source of infection. I combine these two analyses, micro-climatic and demographic, to produce maps of Phoenix that show the locations with the highest likelihood of transmission overall.

DEDICATION

To my Parents

ACKNOWLEDGMENTS

Completing this thesis was achievable through the help of my faculty advisor, Charles Perrings, whose patience and guidance were never underappreciated. Also thanks to my committee members Ann Kinzig, who was instrumental in the formation of the project, and Sharon Hall, who inspired the ecological dimension of this report and whose enthusiasm for this topic motivated its completion. Special thanks to Robert Balling and Mary Whalen for pulling me from the pit of GIS despair, and to Kirk Smith, Laura Adams, and Hayley Yaglom at Maricopa County Vector Control and the Arizona Department of Health Services for providing me with data and support throughout the duration of this project. And of course, I would like to thank my lab-mates in the ecoSERVICES lab for their friendship and support in the last year and a half.

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CHAPTER 1: Mapping regions in Phoenix with climatic conditions necessary to produce dengue transmission.

Abstract Despite the known impact of diurnal temperature range (DTR), or the difference between daytime high and low temperatures, on *Aedes aegypti*'s ability to survive and transmit dengue, it is frequently neglected as an important variable in predicting of the range of both the vector and the disease. DTR is heavily influenced by land cover type. It differs significantly between cities and their surrounding environments and varies widely within an urban area. As DTR decreases, the potential for *Aedes aegypti* to become a dengue-competent vector increases. DTR values decline with increasing atmospheric water content, making areas with an abundance of vegetation and/or standing water more likely to produce dengue-competent mosquitoes. An assessment of the variation in land-use type across metropolitan Phoenix reveals locations where DTR is lowest and where *Aedes aegypti* is most likely to be able to transmit dengue. Micro-climatic information gathered from weather stations across the Phoenix-metro area in combination with NDVI images make it possible to identify these regions in the city.

INTRODUCTION

Dengue virus (DENV), a *flavivirus,* is one virus among several others transmitted by the mosquito vector, *Aedes aegypti*. There are four major serotypes of dengue – DENV-1, DENV-2, DENV-3, and DENV-4 – each differing in virulence and often co-circulating with one another in human populations (Messina, 2014). Dengue is characterized clinically as a febrile illness, with symptoms including mild-to-high fever, joint and muscle pain, rash, and headaches. It normally lasts no longer than one week. Further complications of illness can occur if someone already infected with dengue contracts a different serotype of the virus, leading to what is known as dengue hemorrhagic fever (DHF) or dengue shock syndrome (DSS). Symptoms of DHF/DSS include severe abdominal pain, persistent vomiting, bleeding from the gums or underneath the skin, septic shock, and can occasionally result in death (WHO Dengue and Severe Dengue Factsheet, 2016). Death caused by dengue is most frequent among children and the infirm, and can happen suddenly and without warning.

No vaccine for dengue currently exists, and the most common methods for managing it involve control of the vector *Aedes aegypti*. In the last few decades of the 20th century, mosquito populations and dengue incidence began to climb steadily worldwide, reappearing where it had long since been eradicated earlier in the century and emerging in others for the first time (Monath. 1994; Messina, 2014; San Martin, 2010; Murray 2013; Gubler, 2004). Combating *Aedes aegypti* has proved a formidable task. The mosquito is now established in 128 countries, 100 of which report endemic dengue (CDC). Resurgence can, in part, be attributed to changes in public health policy, most notably the banning of DDT and the subsequent rebound in *Aedes aegypti* mosquito populations (Gubler, 1998). In some parts of the world, *Aedes aegypti* has likewise developed resistance to many of the standard mosquito larvicides and insecticides used against it, further complicating mitigation efforts (Montella, 2007; Rawlins, 1995; Lima, 2011; Werth, 1999; Rodriguez, 2002).

According to the WHO, half the population of the planet is at risk of contracting dengue. An estimated 100 million cases are reported each year, roughly 25,000 of which are fatal (WHO Dengue and Severe Dengue Factsheet, 2016). The majority of dengue cases come from the tropics in Latin America – specifically from the Caribbean– and Southeast Asia, but the range of the disease has grown most rapidly in the Earth's subtropical zones (Wu, 2009; Murray, 2013; Guzman, 2010; Bhatt, 2013). While countries like Brazil and Mexico are experiencing record numbers of dengue cases, the Middle East and South Asia have developed considerable dengue problems of their own (Siqueira, 2016; Paxiao, 2015; Dantes, 2014; Khormi, 2011; Al-Gamadi, 2009; Tyagi, 2004; Rasheed, 2012). International travel, made easy by air transport, is known to have had a significant impact on the spread of dengue around the world, while the global dispersion of *Aedes aegypti* has likewise been linked to international trade (Wilder-Smith, 2005; Wilder-Smith, 2008; Reiter, 1987).

The wide range of *Aedes aegypti* can be attributed in large part to its anthropophilic nature (its preference for human habitats) (Bhatt, 2013; Gubler, 2004). More specifically, *Aedes aegypti* demonstrates preference for urban over rural and agrarian landscapes (Maciel-de-Freitas, 2006). Because climates within cities often differ significantly from the surrounding climate, conditions conducive to the perpetuation of *Aedes aegypti* mosquitos can be found in regions that would otherwise be inhospitable for this species (Jenerete, 2015; Hall, 2016). Major cities in the United States have tend to similar interior climates regardless of their surrounding ecosystem, showing general trends toward similar humidity and temperature (i.e. a city in a desert is more humid than the surrounding ecosystem and a city in a tropical environment is less humid than its surrounding ecosystem) (Hall, 2016).

Given that *Aedes aegypti'*s competency as a vector for dengue hinges predominantly on variations in local climate, the same phenomenon can also be suggested as a reason for why dengue has become endemic in climate zones previously thought to be outside of its potential range (Richardson, 2013; Liu-Helmersson, 2014). Until recently, regional mean temperature and vapor pressure have been the primary climate variables used in range projection for dengue (Hales, 2002; Watts, 1986). Many of these projections use values based on highly controlled laboratory experiments (some of which date back to 1986) and therefore fail to acknowledge the importance of daily variance in temperature and its potential effect on dengue transmission. Because *Aedes* *aegypti* mosquitoes, and other arthropod disease-vectors, are ectothermic, they are highly sensitive to temperature changes throughout the day, and projections that neglect to factor this information into potential dengue range size are not reliable (Lambrechts, 2011, Paaijmans, 2009).

Diurnal temperature range (DTR), or the difference between daytime high and low temperatures, has been shown to have a significant impact on the ability of a variety of arthropods to transmit diseases. Specifically, the longevity of *Aedes aegypti* and its ability to transmit dengue is strongly correlated with both mean temperature and DTR. Given an optimum mean temperature of about 26-30˚C, the potential competence of *Aedes aegypti* increases as DTR values decrease (Carrington, 2013; Carrington 2013; Lambrechts, 2011). Variance in DTR between seasons is believed to be associated with high and low dengue transmission periods in regions where seasonal temperature variation is low, and average daytime temperatures are relatively consistent – for instance in the equatorial regions of the planet (Lambrechts, 2011).

Experimental evidence suggests that declining DTR values can increase the competency of *Aedes aegypti* as a vector for dengue by increasing the likelihood that the virus would situate itself inside the midgut of a mosquito after it had taken a blood meal from an infected organism (Costa, 2011; Carrington, 2013; Carrington 2013). Once in the midgut, the rate of maturation and replication of the virus is more closely related to mean temperature than to variance in temperature, and given enough time it will disseminate into the rest of the body of the mosquito, making the mosquito infectious when it reaches its salivary glands (Costa, 2011; Carrington, 2013; Brady, 2013). Since the lifespan of *Aedes aegypti* also increases when DTR values decline, lower DTR values increase the likelihood that mosquito longevity will meet the time required for the extrinsic incubation period (EIP) of dengue. The EIP, defined as “the interval between the acquisition of an infectious agent by a vector and the vector's ability to transmit the agent to other susceptible vertebrate hosts”, for dengue can be anywhere from 2 to 33 days for mean temperatures between 25-30˚C, decreasing as temperatures increase (*Aedes aegypti* mosquitos have an average lifespan of 8-10 days at 24.4 ˚C) (Medical Heritage Dictionary, 2007; Chan, 2012; Tjaden, 2013).

The relationship between increasing vector competency and decreasing DTR may in part explain the preponderance of dengue in cities compared to rural and wild areas where *Aedes aegypti* populations are relatively similar across each ecosystem type (Maciel-de-Freitas, 2006; Gomes-Dantes, 2009).Cities tend to have DTR values lower than their surrounding environments for two main reasons. One of these is the urban heat island (UHI) effect, caused by the fact that the materials used in built environments, i.e. asphalt and concrete, retain heat more efficiently than the surrounding natural environment. Urban centers re-radiate heat acquired during the day back into the environment throughout the night in quantities far greater than rural or wild landscapes (Balling, 1987). The second cause of differences in DTR within cities due is heterogeneity of the urban landscape (Jenerette, 2015; Kaplan, 2014; Li, 2015). Variations in land-cover features facilitate the establishment of a range of micro-climates, each corresponding to the abundance and type of vegetation, buildings, roads, soil, and water.

This thesis focuses on the second driver of DTR and, in particular, on the effect of variation of vegetation. Within ecology, most work on the topic focuses on the role of trees. As percent tree cover increases, daytime temperatures are reduced relative to the surrounding built environment. Areas with high tree cover have also been shown to have higher heat retention at night when compared to different land-surface types (barring materials like asphalt and concrete), having the effect of narrowing the DTR in regions in a city where tree cover is high (Jenerette, 2015).

This phenomenon can be attributed to the fact that trees remove water from the ground and pump it out into the air (Chapin et al 2011). Because the specific heat of water is so large (4.17 J/g ˚C), it takes more energy to heat the atmosphere where water vapor content is high than it does where it is low, so reducing daytime temperatures in places with abundant trees. Heat acquired by water is lost at similar rates to those in which heat was gained if external environmental conditions are the same, therefore the heat that is acquired by an atmosphere high in water content during the day is more readily retained than it would be in arid conditions, aiding in a reduction in DTR. It follows that highly vegetated areas in a city would have lower DTR values than areas with lower vegetative cover that are also not mostly composed of asphalt and concrete, theoretically increasing the likelihood of dengue transmission in those places with more vegetation.

Vegetation types differ in their capacity to contribute water to the atmosphere, suggesting that areas abundant in mesic plant species would have higher atmospheric water content, and therefore lower DTR, than areas with a higher proportion of xeric plant species. Areas without concrete and asphalt and with little to no vegetation within a city would be expected to have higher DTR values than areas with either xeric or mesic vegetation. Although urban ecosystems are unique in their influences on climate, ecosystems absent man show some similar trends in DTR variance, where bare earth with little-to-no vegetation produces high DTR values and DTR values decrease as vegetation is added. Tropical rainforests, where biomass and vegetative abundance are highest relative to any other terrestrial ecosystem, produce the lowest DTR values on this scale (Chapin et al 2011).

Other factors that increase atmospheric water content are high moisture content in soil (related to vegetation), precipitation, and cloud cover. All are similarly associated with a decrease in DTR (Zhou, 2004; Dai, 1999; Dai, 1997). These phenomena can vary considerably throughout the year, and a reduction of DTR during rainy periods has been suggested as the reason for the seasonal variation of dengue in Southeast Asia, and presumably other parts of the world (Carrington, 2013). A highly vegetated area inside a city during a period of high precipitation and continuous cloud cover would, according to these parameters, have the lowest relative DTR and therefore highest likelihood of *Aedes aegypti* mosquitos becoming dengue competent compared to different parts of a city and different times of the year.

The heterogeneity of metropolitan Phoenix's urban landscape produces a variety of micro-climates, and as suggested previously, the likelihood that some regional micro-climates will produce the conditions necessary for *Aedes aegypti* to become competent as a dengue vector is higher than others. Using diurnal temperature range as the primary factor in determining *Aedes aegypti* mosquitoes' capacity for transmission, the study aims to identify those areas in the Phoenix metropolitan area where the vector is most likely to be competent, and therefore cases of locally acquired dengue are most likely to occur.

Information provided herein will allow for more specific targeting of mosquito populations for mitigation and eradication by agencies like Maricopa County Vector Control, enabling a more efficient use of resources and further decreasing the likelihood that dengue will be transmitted within state borders. Maricopa Vector Control currently uses mosquito reporting rates from citizens and numbers of mosquitos recorded at trap sites to establish primacy regarding which areas in the city to focus vector control efforts. Reliance on citizen reports of mosquitoes raises questions regarding equitable allocation of vector control resources across the city (i.e. some groups of people are more likely than others to voice complaints or expect government intervention in circumstances like these), and Maricopa County Vector Control's small department size calls into question their ability to monitor the over one thousand traps across the Phoenix metropolitan area with consistency and accuracy.

Using the climate based dengue surveillance methods suggested in this report alleviates both of these limitations in current vector control tactics and increases precision of existing climate based surveillance techniques. While this chapter uses only one index (vegetation) to capture DTR values, the implication is that any environmental element known to influence DTR should be considered as a viable metric by which to delineate the areas within cities most at risk for dengue transmission. Because DTR information is not used in remote sensing dengue surveillance monitoring methods, this research contributes a relatively novel approach to combat the virus and has applications that are only just now beginning to be realized.

STUDY AREA AND METHODS

Site Description

The Phoenix metropolitan area is the largest urban area in Arizona. Located in the Sonoran Desert, it is home to roughly 60% of Arizona's total population (4.33 million people), and has an area of more than 9,000 square miles. In general, Phoenix has a hot, subtropical desert climate, and there are a variety of factors contributing to microclimatic differences throughout the city. Because Phoenix is a well-studied location for research on urban ecology and the urban heat island (UHI) effect, the influences that vegetation and built infrastructure have on regional climate have been thoroughly examined. Vegetation has been found to contribute to lower both the mean temperature and diurnal temperature range (DTR) of a region, with this phenomenon being most pronounced in areas with an abundance of tree cover.

In the Phoenix metropolitan area, the percentage of tree cover is highly associated with neighborhood wealth, where poorer neighborhoods have significantly fewer trees than the more well-to-do neighborhoods. Areas of highest tree abundance include Central Phoenix, Arcadia (Camelback Mountain area), Scottsdale, Paradise Valley, portions of Mesa and Chandler, and in Tempe on and around the Arizona State University campus. Regions in the city with a notable lack of tree cover include South Phoenix, West Phoenix, South Glendale, and the Gateway District (an area along the light-rail corridor near Sky Harbor International Airport between (See the dark blue areas of Map 1.1).

The city and surrounding region experience two rainy periods each year, one in the summer and one in the winter. The summer monsoon season in Phoenix is characterized by thunderstorms with short but intense bursts of rainfall that are more likely to cause damage from flooding and wind than winter rains are. The winter monsoon is characterized by showers with less intense but more prolonged periods of rainfall. Diurnal temperature range reaches its lowest point during the summer monsoon and is consistently lower during this period than all other times of year across the entire metropolitan area. DTR values begin to decline sharply in the middle of June, at the beginning of the monsoon season, and reach their lowest values in July. DTR remains relatively low in August and September compared to the rest of the year, but begins a slow ascension after July. The summer monsoon rains typically culminate at the end of September, after which DTR begins to steadily climb.

Weather and Temperature Sensors

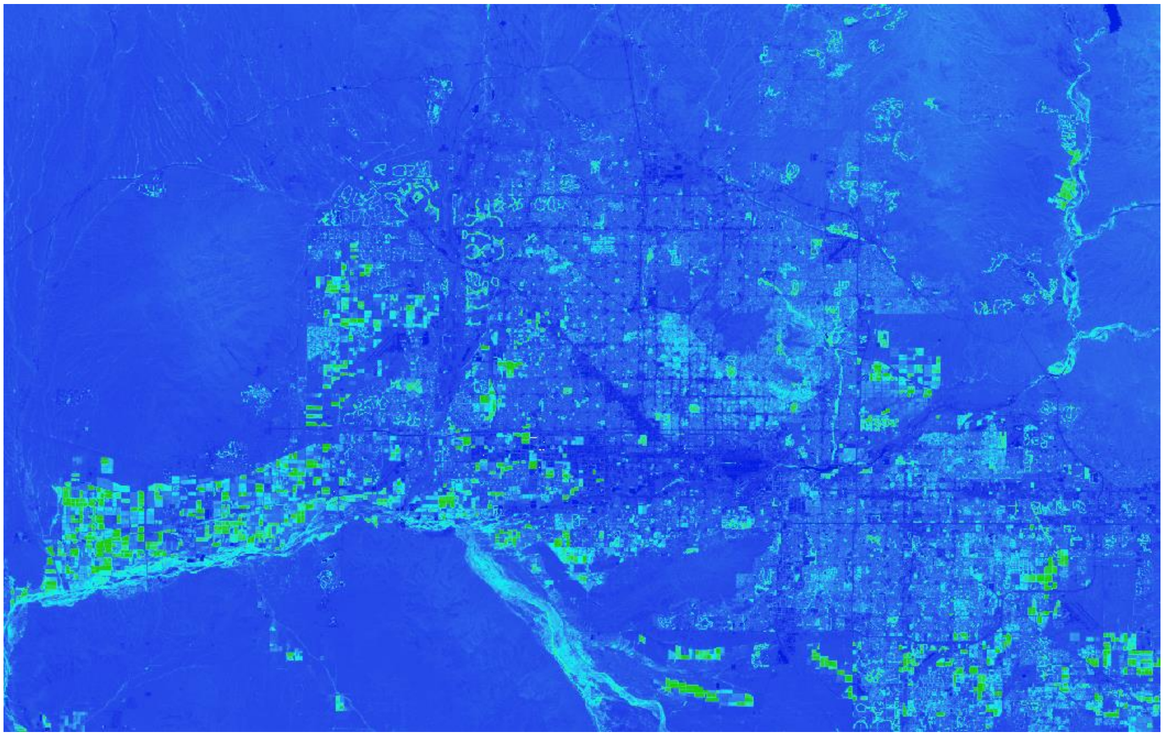
A total of 25 weather sensors were used to gather daily information about temperature and climate in specific locations (Figure) throughout the Phoenix-metro area (7 from Maricopa County Flood Control (MCFC), 9 from ASU used urban ecology research, 6 from the National Climate Data Center (NCDC), and 3 from the Arizona Meteorological Network (AZMET)). The weather sensors used by MCFC, the NCDC, and AZMET were all located in areas ranging from roadsides and parking lots to neighborhood parks and golf courses. Residential areas were often not expressly covered by this data, however several golf courses with temperature sensors were in residential neighborhoods. The 9 sensors used by the ASU faculty were specifically chosen to represent a variety of residential yard-types throughout the city.

For all 25 sensors, the maximum, minimum, and mean temperatures were recorded each day, as well as incidence of precipitation. Due to the relatively recent placement of the weather sensors used by the ASU urban ecology researchers, the longest period for which each sensor had data for the same amount of time was from March 30, 2013 – August 20, 2014. Each ASU sensor recorded information for at least this period of time, and MCFC, NCDC, and AZMET sensors had data ranging from several years to more than a decade prior. The DTR for each weather sensor was plotted over this period (March 30, 2013 – August 20, 2014), and confirmed that from July 2013 through September 2013 the DTR for each one was consistently lower than all other times of the year. DTR was then averaged over the entire period (March 30, 2013 – August 20, 2014) and this relatively low period (July 1, 2013 – September 30, 2013) for each sensor.

NDVI

Vegetation in Phoenix was mapped using normalized difference vegetative index (NDVI) data for the city and metropolitan area. This study used Landsat Thermic Mapper (TM) images of Phoenix from June 2011 with a pixel resolution of 30x30m. Based on the definition from the Central Arizona Phoenix Long Term Ecological Research Project (CAP LTER) (See Map 1.). NDVI combines the Near Infrared (NIR) and RED bands from the Landsat Image using the formula: (NIR – RED)/ (NIR +RED). NIR is band 4 (0.76- 0.9 micrometers) and RED is band 3 (0.78-0.82 micrometers). The NDVI formula was applied to the image. The range of possible values is -1 to +1. In the Landsat Thermic Mapper (TM) images of Phoenix the lowest NDVI value is -0.9722 and the highest is 0.7797.

Only one Landsat image was used, and therefore the study implicitly assumes that NDVI values are fixed in time. The June 2011 image was selected as representative of summer the land use and vegetative cover in Phoenix. NDVI was measured for each 30x30m pixel (900m^2). Around each weather sensor average NDVI values were recorded over increasing areas: 9 pixels (8,100m^2), 25 pixels (22,500m^2), 49 pixels (44,100m^2), 81 pixels (72,900m^2), 121 pixels (108,900m^2), and 169 pixels (152,100m^2).



Map 1.1) NDVI map of the Phoenix metropolitan area and portions of the surrounding desert. On a scale from -0.9722 to 0.7797, where lowest normal difference vegetative index is -0.9722 and highest is 0.7797, increasing vegetation is indicated by a transition from blue to green (Data provided by the Central Arizona Phoenix Long Term Ecological Research Project).

Regression Analysis

DTR was then modeled as a function of NDVI. Specifically, DTR was regressed against NDVI using IBM's SPSS statistics software. Scatter plots displaying the relationship between NDVI at each pixel scale (1, 9, 25, 49, etc.) and DTR are shown in Figure 1.1. Each scale of NDVI was tested against DTR to determine the significance of the relationship between the two, revealing 25 pixels (22,500m^2) to be the most significant pixel scale.

The existing literature on vegetative influences on diurnal temperature range in urban areas suggests that the regression would be functionally represented best by a quadratic curve. Low NDVI values indicating built environments produce low DTR, slightly larger NDVI values indicate less of a built environment but also a scarcity of vegetation that increase DTR and an increase in tree canopy cover indicated by high NDVI values would mean another subsidence of DTR (Hall, 2016; Jenerette, 2015; Chapin et al, 2011; Balling, 1987). In Phoenix, however, the highest NDVI values area associated not with tree cover, but with agricultural fields or gold courses. Since these are characterized by some of the highest DTR values in the entire data set, their inclusion means that the best fit is a cubic function, which is incongruent with what is expected. This phenomenon i greater detail in the results.

Expected:

$$DTR_i = b_0 + b_1 NDVI_i + b_2 NDVI_i^2 + e$$

Actual:

$$DTR_i = b_0 + b_1 NDVI_i + b_2 NDVI_i^2 + b_3 NDVI_i^3 + e$$

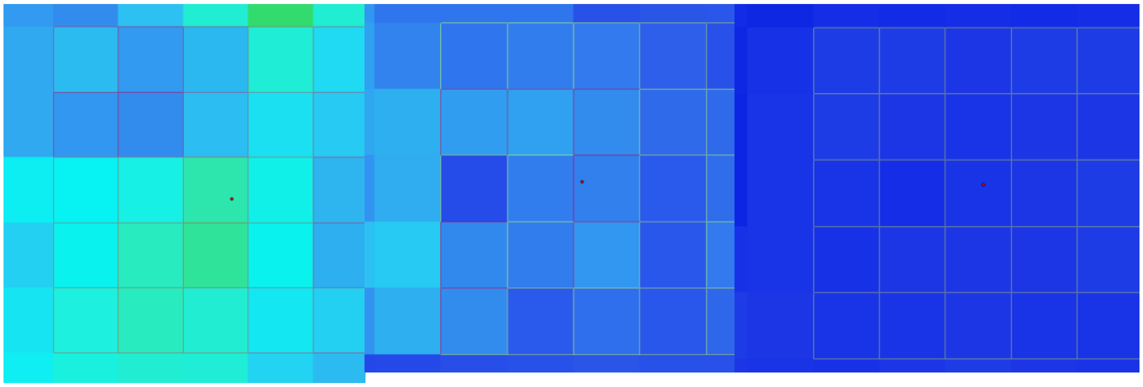
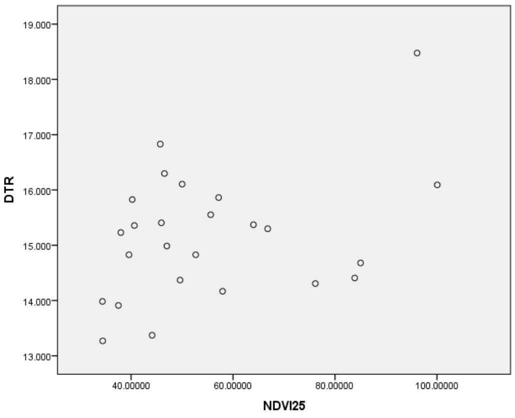


Figure 1.1) Examples of 3 weather sensors located in various environments as depicted by their NDVI values. High NDVI values indicating high vegetative cover (left) are green

and become bluer as the vegetation becomes more moderate (middle). Very low NDVI values (right) display pixels with darker blue colors and have little to no vegetation.



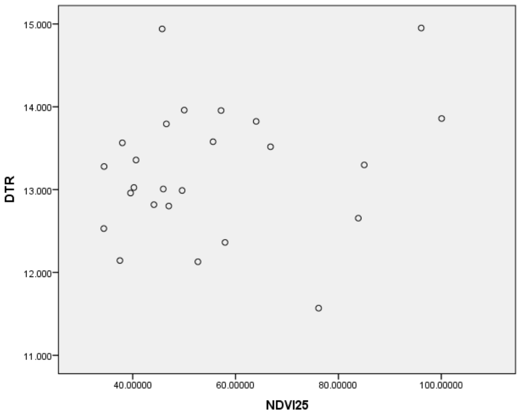


Figure 1.2 (left) Scatter plot of the 25 sensors used to determine a statistical correlation between NDVI and DTR, with DTR values averaged at each sensor for a year and a half (March 2013-August 2014). **Figure 1.3 (right)** Scatter plot of the 25 sensors used to determine a statistical correlation between NDVI and DTR, with DTR values averaged at each sensor for one summer (July 2013-September2013). DTR values for the entire city decrease in the summer, bringing the stations that had some of the highest DTR values for the year-and-a-half average closer to the stations with the lower values in the same period. The Low NDVI-Low DTR weather stations in Fig 1.1 do not have a significant change in DTR values in the summer, whereas the stations located in places with moderate NDVI (insert values) decreased in DTR by several degrees. Each sensor reported a decrease in DTR during the summer months.

Reclassifying NDVI data based on regression analysis

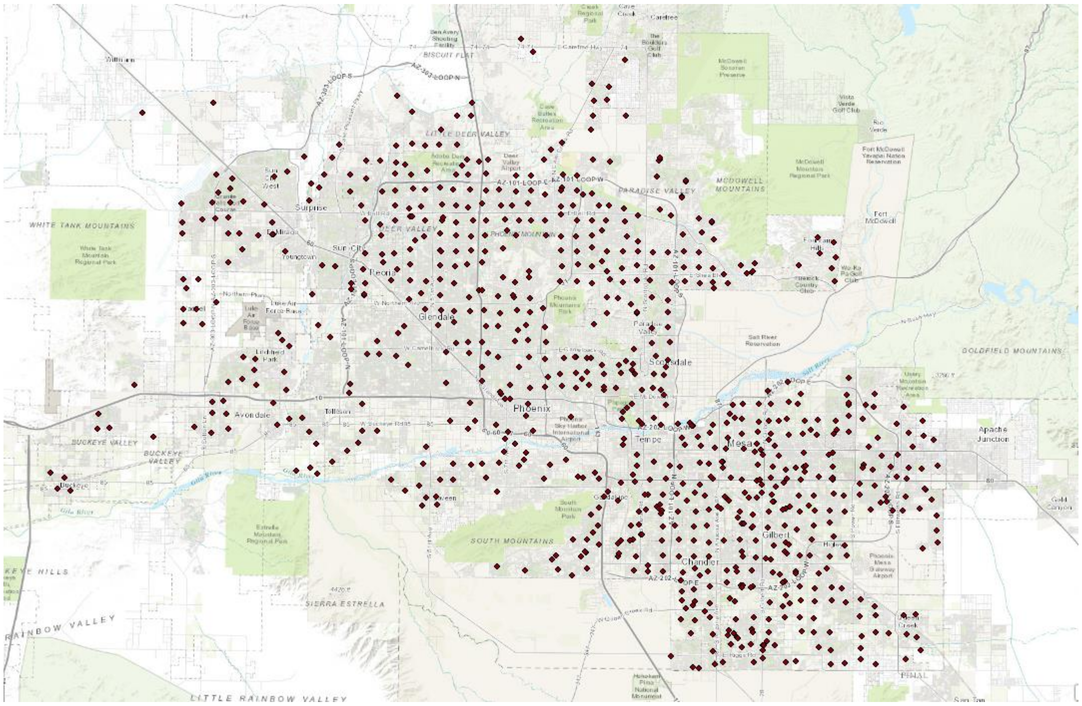
The correlation between moderately high NDVI and relatively low diurnal temperature range values was then used to identify the areas within Phoenix with the highest potential for *Aedes aegypti* to become a competent vector for the dengue virus. The location on the fitted curve where the slope is identifiable as a local minimum $\left(\frac{dDTR}{dNDVI}=0,\frac{d^2DTR}{dNDVI^2}>0\right)$ was used to identify the NDVI values for which the both the

NDVI and DTR conditions are optimal for dengue transmission. These pixel values on the NDVI raster were then used to reveal the greatest dengue-risk locations in the city. Values on either side of the local minimum were included in the NDVI raster reclassification to display areas of secondary risk. This gave a range of NDVI values to display risk over the Phoenix metropolitan area.

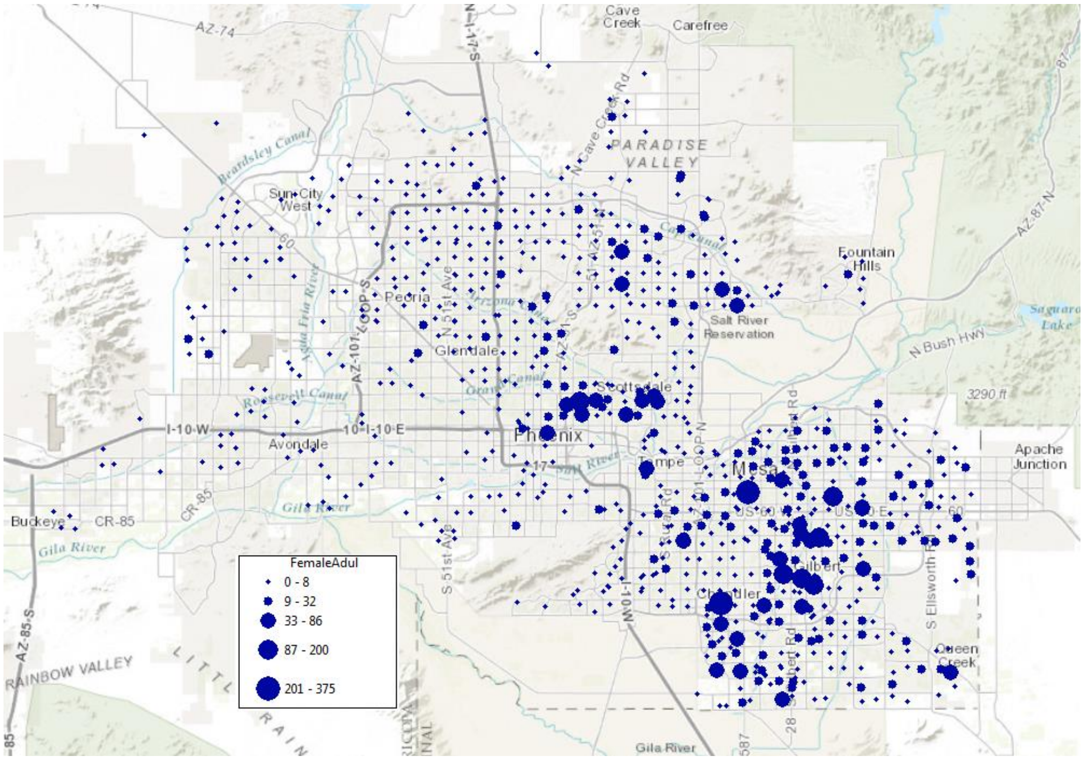
Mosquito Abundance Data

Maricopa County Vector Control (MCVC) monitors mosquito abundance in the Phoenix metropolitan area by periodically collecting mosquito specimens from close to 1,000 traps located throughout the city. Traps are ideally placed within 1 square mile of each other, and areas that record higher abundances of mosquitoes, as well as places where mosquito related issues are reported to MCVC by citizens, are allocated a greater density of traps. Similarly, areas where there are fewer recorded mosquitos and where there are fewer citizen reports receive less attention (See Map 1.2.1).

Because data received for this thesis from Maricopa County Vector Control shows yearly cumulative numbers for each trap, mosquito density and abundance cannot be interpolated. A “hotspot” map was generated to show the locations in the Phoenix metropolitan region showing the traps reporting the highest number of female adult *Aedes aegypti* mosquitos (only females are capable of transmitting dengue) in 2015 (Map 1.2.2). Multiple locations appearing as on this map showing the highest number of mosquitos consistently record the highest numbers relative to elsewhere in the city, while several locations that have frequently recorded high numbers of female adult *Aedes aegypti* mosquitos in the past are not represented as such in the 2015 data. It is argued here that, in addition to risk determined by *Aedes aegypti*’s abundance in an area, the likelihood that they can become infectious can be inferred with this data when joined with the information used to generate Map 1.3 (See Map 1.4).



Map 1.2.1) Distribution of Maricopa County Vector Control mosquito-trap locations. (Data provided by Maricopa County Vector Control).



Map 1.2.2) Mosquito traps in the Phoenix metropolitan area showing the highest number of trapped mosquitoes throughout in 2015. The legend indicates the highest recorded numbers range between 201 and 375, but multiple traps reported higher numbers as indicated in **Figure 1.7**. They are expressed in this map as the same size as those in the 201-375 range. (Data provided by Maricopa County Vector Control).

RESULTS

Using NDVI as a proxy for DTR: Showing statistical correlation

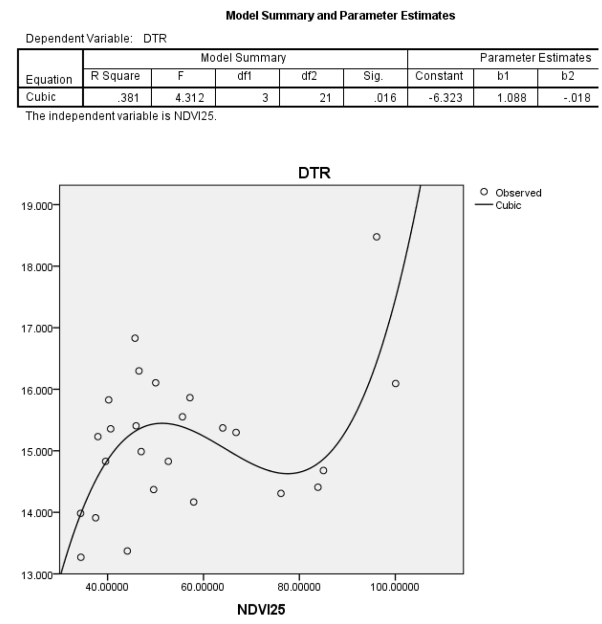
For both the full-year DTR average and the summer-month DTR average, regression models of the relation between NDVI and DTR were estimated for each pixel scale of NDVI values around every temperature sensor (1 30x30m pixel (900m^2), 9 pixels (8,100m^2), 25 pixels (22,500m^2), 49 pixels (44,100m^2), 81 pixels (72,900m^2), 121 pixels (108,900m^2), and 169 pixels (152,100m^2)), for a total of 14 regressions (Regressions for each pixel scale for the full year can be found in Appendix A, and regressions for each pixel scale for the summer months can be found in Appendix B). In all cases a cubic model fitted the data best, especially for the full-year DTR average.

Models based on NDVI values averaged on a scale of 25 pixels showed the highest statistical significance for both the full-year DTR average and the summer-month DTR average. For the regression model based on 25-pixel averaged NDVI values and the full-year DTR average, the fitted curve follows the following trend: at extremely low NDVI, the DTR is similarly extremely low (consistent with expectations based on the urban heat island effect), then as NDVI begins to increase in value, so does DTR. Up until NDVI values of around 0.085, NDVI and DTR show a positive correlation. At NDVI values ranging from 0.08 to 0.09, the fitted cubic curve zeros out at a local maximum, and then increasing NDVI values begin to be more closely associated with decreasing DTR values. Until NDVI values of ranging from 0.266 to 0.309, NDVI and DTR values negatively correlate. The fitted cubic curve zeros out at local minimum with an associated NDVI value of 0.285.

According to the theory of increased dengue transmission rates being exclusively a result of low DTR, this highlights NDVI values at -0.03 (extremely low NDVI representing low levels of vegetation and an abundance of concrete and asphalt) and 0.285 (moderately high NDVI representing leafy suburban neighborhoods with an abundance of trees) as areas of interest when trying to delineate areas of potential dengue transmission assuming the predictive capability of these regressions.

The fitted model for predicting DTR based on NDVI for the full year is:

$$DTR_i = -6.323 + 1.088 NDVI_i + -0.018 NDVI_i^2 + 9.106e^{-0.005} NDVI_i^3 + e$$

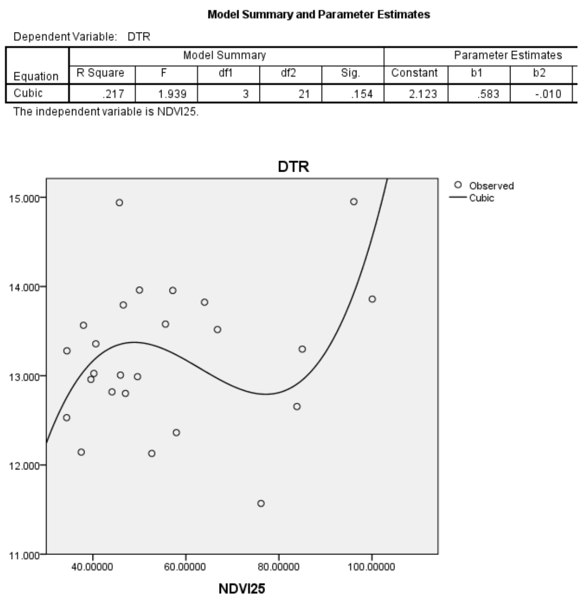


Model Summary and Parameter Estimates

Dependent Variable: DTR

Equation	Model Summary					Parameter Estimates		
	R Square	F	df1	df2	Sig.	Constant	b1	b2
Cubic	.381	4.312	3	21	.016	-6.323	1.088	-.018

The independent variable is NDVI25.



Model Summary and Parameter Estimates

Dependent Variable: DTR

Equation	Model Summary					Parameter Estimates		
	R Square	F	df1	df2	Sig.	Constant	b1	b2
Cubic	.217	1.939	3	21	.154	2.123	.583	-.010

The independent variable is NDVI25.

Figure 1.4 (left) A cubic function fitted to the NDVI-DTR data with DTR averages taken from all 25 sensors for a year and a half (March 2013-August 2014) is represented by

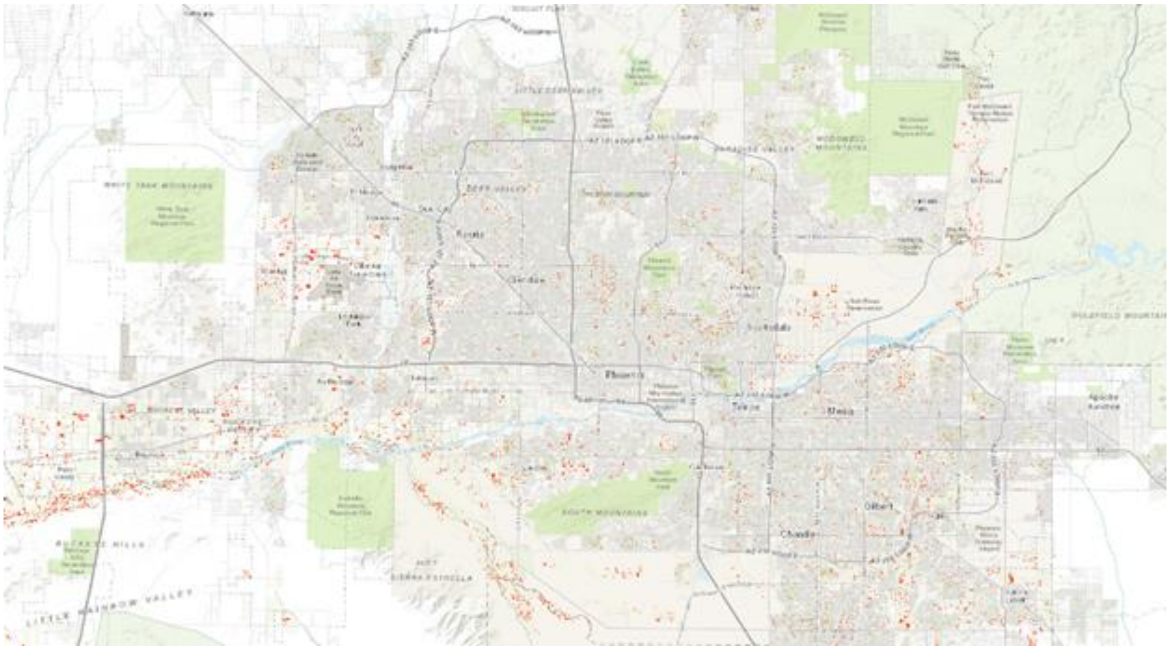
$$DTR_i = -6.323 + 1.088 NDVI_i + -0.018 NDVI_i^2 + 9.106e^{-0.005} NDVI_i^3 + e$$

Figure 1.5 (right) A cubic function fitted to the NDVI-DTR data with DTR averages taken from all 25 sensors for one summer (July 2013-September 2013)

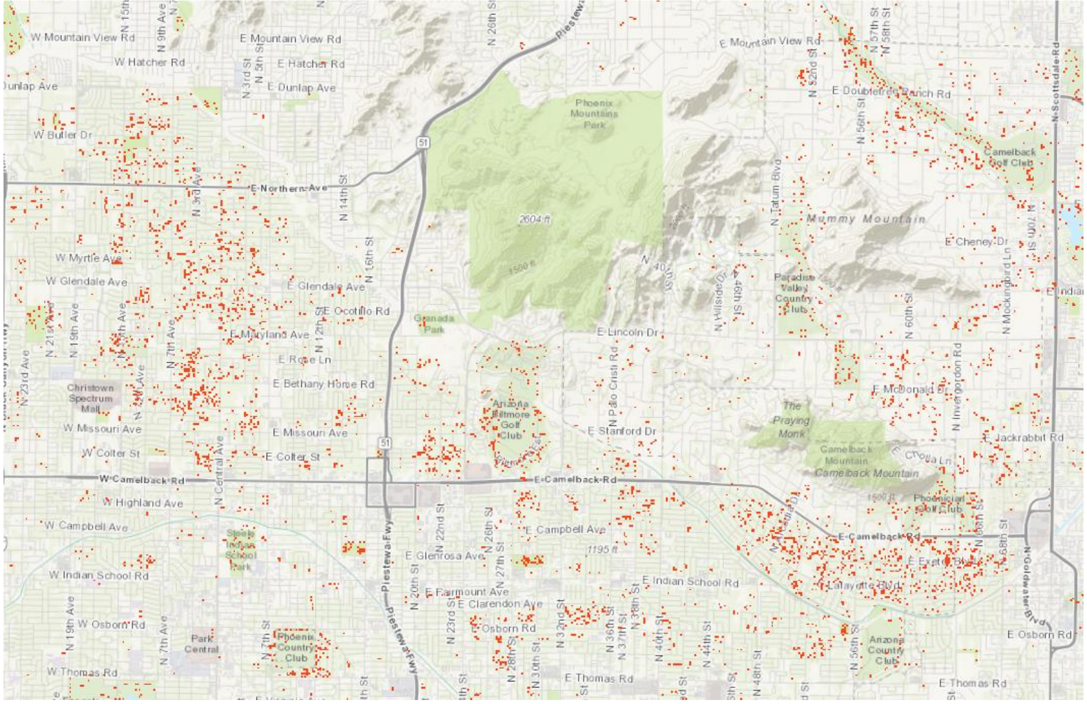
Maps with NDVI values consistent with low DTR

The local minimum on the cubic curve function used to fit the NDVI-DTR data that exemplifies high NDVI and low DTR has a normalized NDVI value of 77.5, or a non-normalized value of 0.285. The range of NDVI values for the study area, based on the Landsat Thermic Mapper (TM) images of Phoenix, are from -0.9722 to 0.7797. In order to identify the locations in the city with environments that produce the relatively lowest DTR values, excluding the extremely low NDVI areas, the values on Landsat

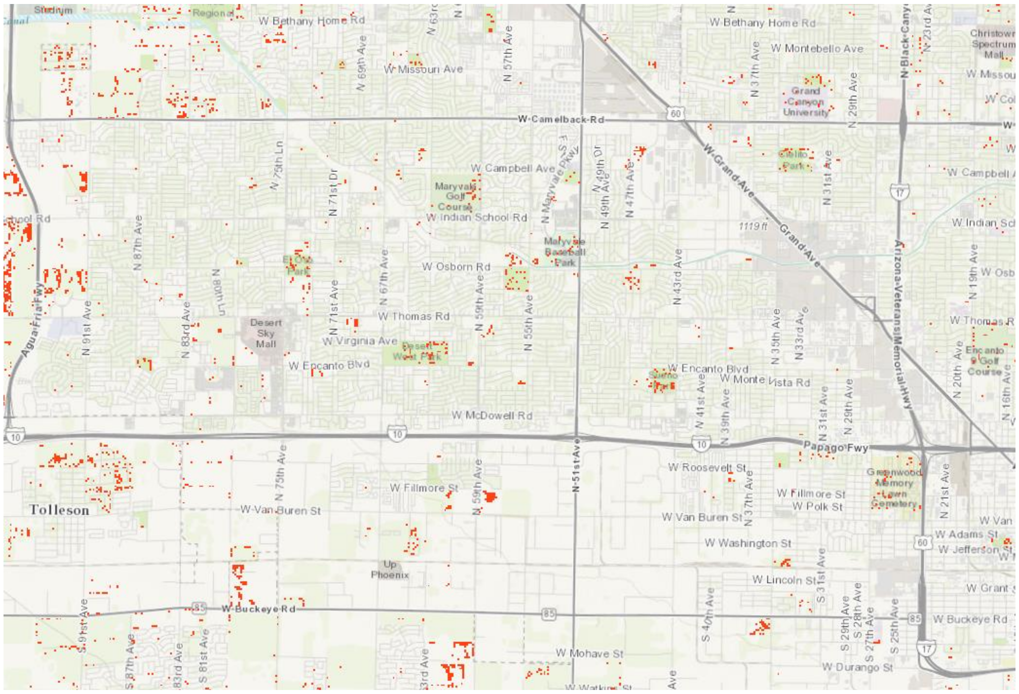
Thermic Mapper (TM) NDVI images of Phoenix existing on a range of (0.266 to 0.309) were visually reclassified and overlaid onto a topographic map of Phoenix (see below).



Map 1.3.1) Phoenix metropolitan area overlaid with areas denoting low DTR based on NDVI values ranging between 0.266 and 0.309.



Map 1.3.2) Zoomed in to more highly vegetated neighborhoods in the city; Arcadia Neighborhood, Scottsdale and Biltmore Neighborhood, Phoenix



Map 1.3.3) Zoomed in to more sparsely vegetated neighborhoods in the city; South Glendale

Showing a Relationship between mosquito abundance and NDVI

The mosquito abundance data used in this report is not at the pixel level, and so cannot be used to spatially display *Aedes aegypti* population density pixel by pixel. Single traps have additive data for an entire year, making it impossible to determine areas where mosquito abundance fluctuates and when and where the mosquito's presence in the city is greatest. Mosquito traps are also not given the same attention across the city, for example *Aedes aegypti* were collected from traps in excess of 20 times in a year in some places and in others were collected once or twice over the same period of time.

In the absence of spatially usable *Aedes aegypti* population data, an attempt was made to determine the relationship between NDVI and abundance of the mosquitos at trap sites. There was no significant correlation between NDVI value and mosquito abundance, but the data did exhibit several features worthy of note. For one, there are four traps between the 0.15 and 0.25 NDVI mark that account for a greater number of mosquitoes than any other trap by a large margin. Also, while not every trap with a low abundance of mosquitoes also had a low NDVI, there is generally a positive relation NDVI and mosquito abundance for NDVI levels below 0.2 (See Figure 1.6)

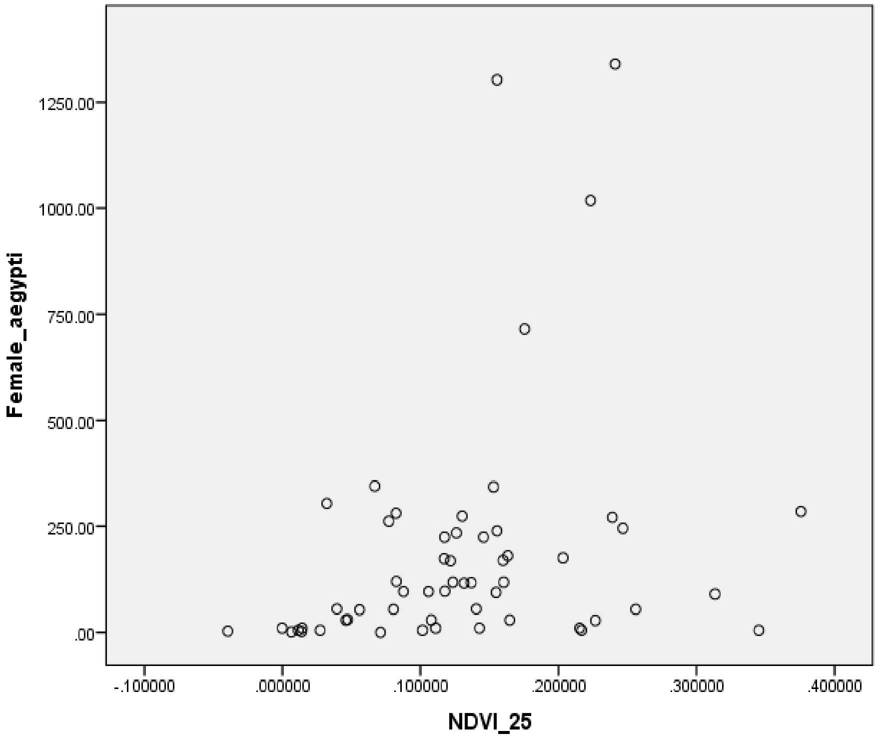
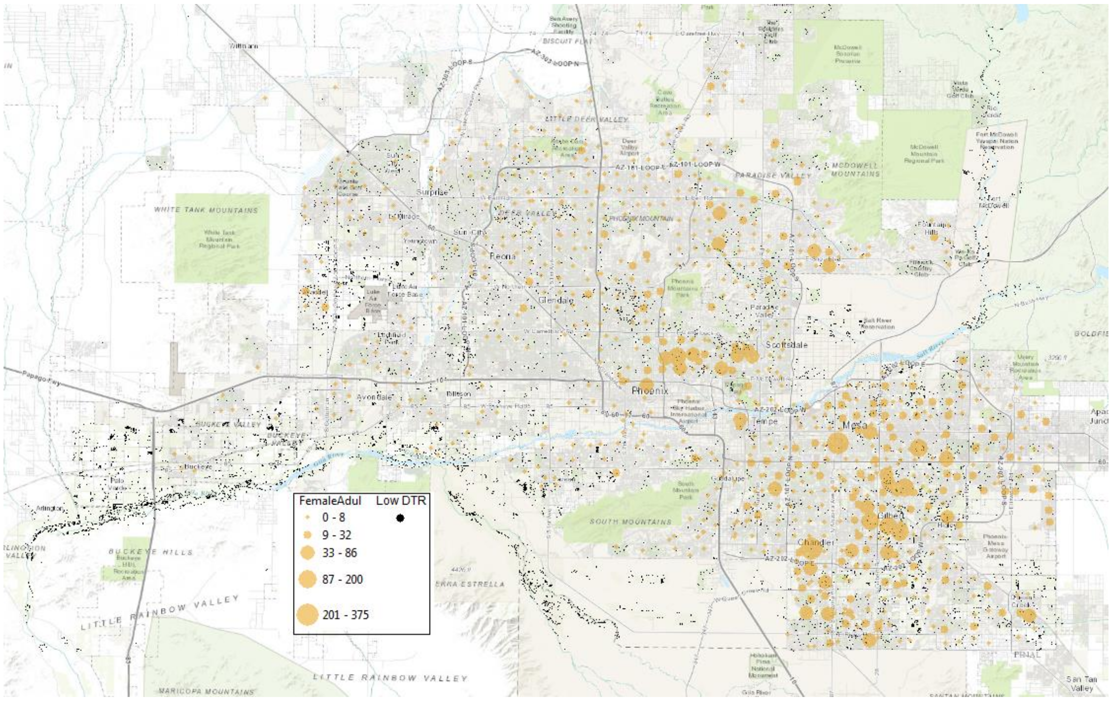
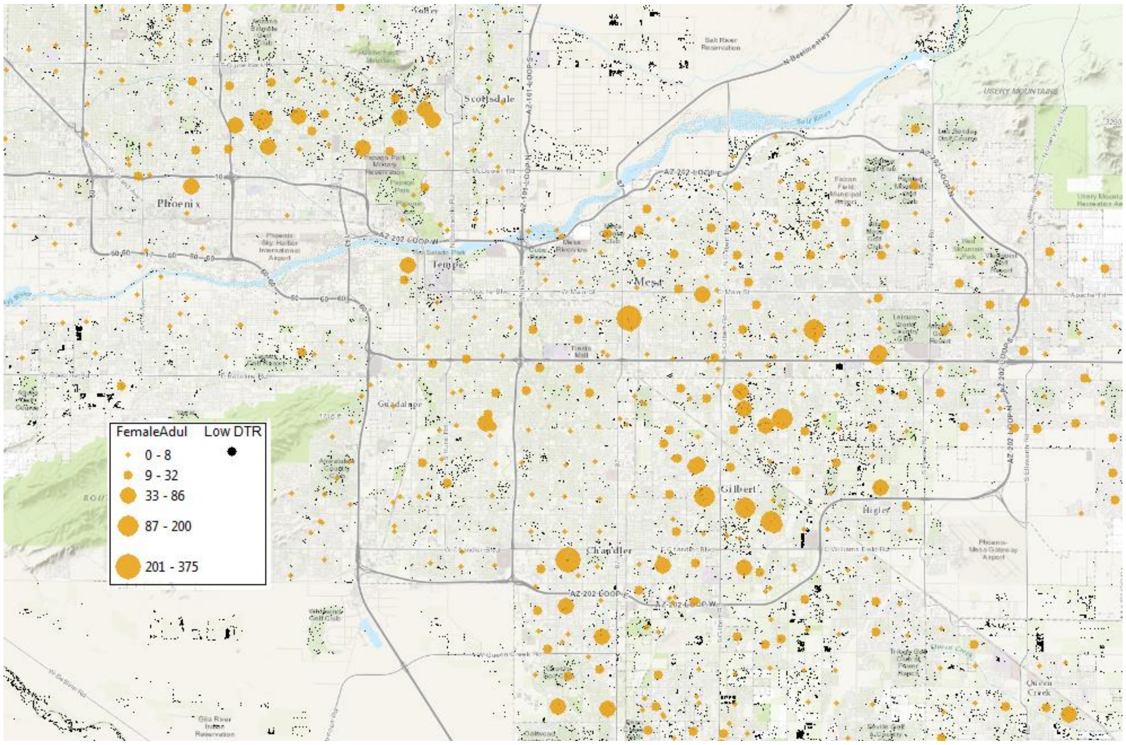


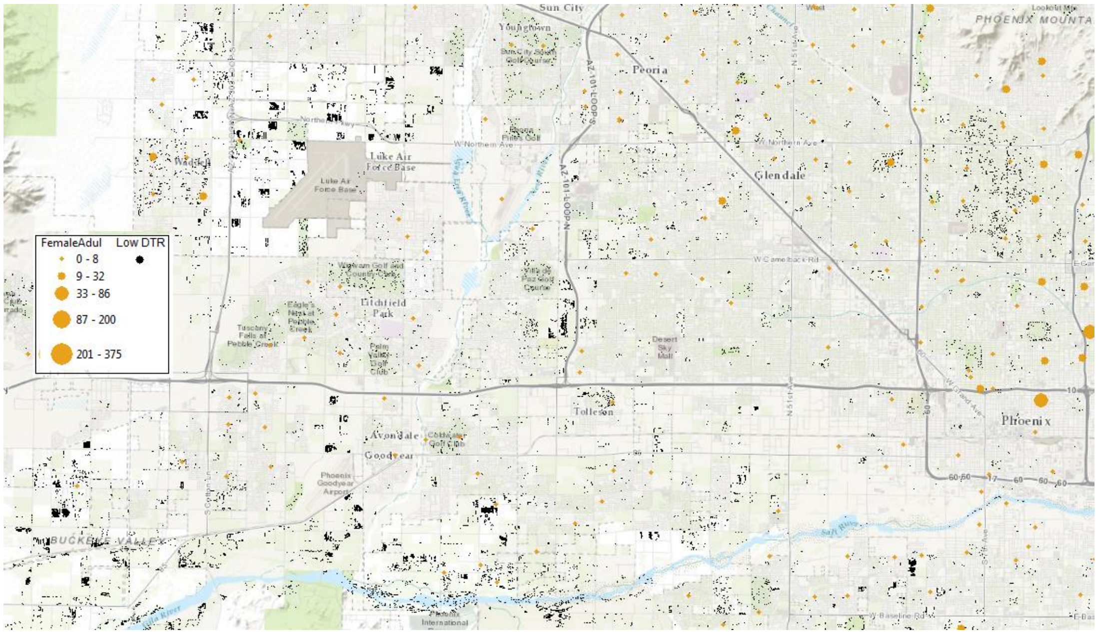
Figure 1.6) Scatter plot displaying mosquito trap sites according to their NDVI and abundance of female *Aedes aegypti*.



Map 1.4.1) 2015 cumulative mosquito trap abundance (orange) overlaid with areas showing low DTR.



Map 1.4.2) Zoomed in 2015 cumulative mosquito trap abundance (orange) overlaid with areas showing low DTR to show areas in the city with the highest recorded numbers of *Aedes aegypti*; East Valley (Tempe, Mesa, Gilbert, and Chandler), and South Scottsdale/Arcadia.



Map 1.4.3) Zoomed in 2015 cumulative mosquito trap abundance (orange) overlaid with areas showing low DTR to show areas in the city with the lowest recorded numbers of *Aedes aegypti*; Central Phoenix and Southwest Valley (Southwest Phoenix, Glendale, Avondale, and Tolleson)

DISCUSSION

In many cities, remote sensing techniques are underutilized by local public health agencies for predicting and mapping disease emergence. This thesis indicates one way in which remotely sensed data can support disease vector control. Based on the hypothesis that the competence of *Aedes aegypti* as a vector for the dengue virus increases when DTR is reduced, a correlation between NDVI and DTR was established and used to determine locations in the Phoenix metropolitan area potentially at risk. Locations in Phoenix that have NDVI values ranging from 0.266 to 0.309 are most likely to offer environmental conditions that enable *Aedes aegypti* to become a competent vector. While I do not have mosquito abundance on the same scale, trap abundance data can be used to indicate which of these locations may be most at risk. This information can then public health authorities to identify priority areas for both mosquito control efforts and epidemiological monitoring.

The influence that daily temperature fluctuations have on the ability of *Aedes aegypti* to transmit dengue does not currently inform models aimed at predicting the range size of the virus, thus providing additional value to these findings. Often, generalized climatic information for entire regions is used as the predictive measure, and analysis of smaller scale climatic conditions is typically neglected. Evidence of the extreme effects that minor changes in temperature can have on the transmission potential of *Aedes aegypti* highlights the need for modeling techniques that use more spatially explicit and localized climate information for prediction. *Aedes aegypti*'s preference for an urban environment, moreover, reinforces the need to use micro-climatic to estimate predictive parameters.

As a qualifying statement, this is most pertinent to regions outside of tropical climate zones. Tropical climate zones typically have low enough DTR values year-round, helping to make dengue endemic, and have normal atmospheric conditions allowing *Aedes aegypti* to be a competent vector. That said, a reduction in DTR in these places during rainy seasons is often accompanied by an increase in dengue incidence, as well as by heightened abundance of *Aedes aegypti.* In these circumstances, more regionally general DTR information is useful when predicting the seasonality of dengue. In fact this is how DTR information is typically used in predictive range mapping for dengue, where incorporation of small-scale DTR variation is virtually non-existent. This information is especially useful in years experiencing rainfall patterns divergent form regional norms, and has relevance wherever there is concern that dengue might emerge or spread.

In Phoenix, the period of the year with the lowest average DTR values are the months during the summer monsoon, more specifically July, August, and September. July has the lowest monthly average DTR, followed by August, and then September. Geographically similar regions to Phoenix, most importantly Sonora, Mexico, report some of their highest incidence rates of dengue in September, indicating that the same might hold true for Phoenix assuming the significance of climate as a primary predictor for the spread of dengue. Abundance of *Aedes aegypti* is also highest during these months due to more frequent rainfall and hence a greater opportunity for the mosquito to breed. As mentioned in the introduction, reduced DTR is also conducive to the longevity and reproductive capability of *Aedes aegypti*, so it would make sense that the reduction of DTR due to seasonal rains would influence mosquito populations.

This seasonal reduction in DTR, however, is not likely enough to produce dengue-competent mosquitoes in Phoenix alone, and it was for this reason that closer examination into the city's micro-climatic variation was necessary. The use of 25 temperature sensors throughout the Phoenix metropolitan area were the method by which this project chose to gain a sense of this variation and link it to vegetative cover. Temperature sensors that recorded the lowest DTR values were nearly always associated with the lowest NDVI values. The locations of these sensors were sparsely vegetated, and comprised mostly of impermeable concrete and asphalt. The high degree of heat retention in concrete and asphalt are notable for possessing prevents regions where they are abundant from cooling down to the same temperatures as adjacent regions where they are lacking or absent. The industrial sector of Phoenix (southwest of downtown) and Sky Harbor International Airport are two regions in the Phoenix metropolitan that are composed of this type of environment. Since mosquito trap sites associated with low NDVI values almost always reported very low levels of mosquito abundance, these Low NDVI-Low DTR regions were not thought to produce a significant risk for dengue transmission (there are problems with the data, however, that complicate the story).

As NDVI values increased, DTR values began to climb. This phenomenon can be attributed not to an increased vegetative abundance, but a decreased concrete and asphalt abundance. Without these artificial materials the environment's ability to retain heat is substantially lessened, and absent of any vegetative canopy the heat loss from these environments is substantial. It is these environmental characteristics in general, coupled with a dry atmosphere, that are largely responsible for the extreme fluctuations in daytime and nighttime temperatures in desert ecosystems. As vegetative cover begins to increase, DTR values begin to decline again. Increased soil moisture that contributes to a greater atmospheric water content is thought to be one of the driving factors in reducing DTR.

As NDVI values near 0.3, DTR values reach a second minimum. The environmental conditions associated with these values on the NDVI scale involve residential neighborhoods with a high percentage of vegetative cover, a significant portion of which is trees. These areas require a much larger investment of water than more sparsely vegetated areas in order to maintain the vegetation. An increase in in the percentage of tree cover likewise means an increase in atmospheric water content for a variety of reasons. In order for water to reach the top-most portion of a tree, the tree creates a vacuum, or pump, facilitated by opening of the stomata in a tree's leaves and the expulsion gaseous H_20 during gas exchange. Water closer to the bottom of the tree acts to replace the water lost through gas exchange and moves upward, thus creating a pump whereby water is extracted from the soil and eventually released into the air. Soil moisture in these places is kept relatively consistent through irrigation, even in periods of drought, thus enabling the continued provisioning of the air with water.

A more extensive canopy has the additional effect diminishing wind speed. This adds to the attractiveness to *Aedes aegypti* of micro-climatic conditions generated by a neighborhood with a high abundance of trees. Any increase in NDVI values beyond the point at which tree cover is at a maximum will have the opposite effect. NDVI values in Phoenix greater than 0.3 tend to be agricultural fields or grassed areas such as golf courses or sports fields. These areas tend to involve greater DTR, higher wind speeds, and lower humidity. It is for this reason that the curve fitted to the NDVI-DTR data was cubic and not quadratic, as NDVI values upwards of 0.3 begin to climb again in DTR.

NDVI values map ranging from 0.26 - 0.30 produce diurnal temperature ranges most likely to favor the spread of dengue. Map 1.3 shows the places in Phoenix where these NDVI values were reclassified from their original numerical assignment and coloration to produce red dots and laid over a topographic map of Phoenix to display areas where dengue transmission as a product of environmental influences is most likely to occur.

At present, Maricopa County Vector Control focuses the majority of its efforts in combating *Aedes aegypti* populations almost exclusively on where mosquito abundance is greatest, and where a majority of mosquito complaints from citizens come from. As these data show, however, the regions in the city that produce the greatest abundance of mosquitoes are not necessarily the ones that produce the greatest risk of creating a dengue-suitable environment. While it is important to try and keep mosquito populations down across the entire city, especially where citizen reports of mosquitos are highest, allocating additional attention to the places revealed in Map 1.3 as producing the greatest risk for dengue emergence based on their micro-climatic conditions would reduce the possibility of dengue emerging in the Phoenix metropolitan area.

While Phoenix's unique climate relative to the rest of the United States might be thought to limit the wider usefulness of an NDVI-DTR model for determining areas where dengue has the highest probability of being transmitted, the essential similarity of cities suggest that it could be helpful in many other locations. That said, the NDVI values specified as producing the greatest risk in Phoenix are unique to the city. They are typically associated with the greatest density of vegetation and account for the greatest biomass (trees), but as already mentioned they do not represent the highest values on the NDVI scale. Grassed areas and agricultural fields account for the highest values on Phoenix's normal difference vegetative index, and these land-use types were identified as having very high DTR values. In other cities, places at risk for dengue emergence might have vegetative configurations that equal or exceed Phoenix's highest NDVI values, but may not be primarily agrarian or composed of grass. A model using NDVI as a proxy in an environment like this would likely show more resemblance to a parabolic function than a cubic one.

Regional discrepancies like this are to be expected when configuring a model detailing an environment's influence on the potential emergence of a disease, but so long as a suitable method for determining regional variance in DTR is established, this surveillance technique may apply to many more vector borne diseases than dengue. As evidence of the link between diurnal temperature range and the transmission of vector-borne diseases is substantiated, public health agencies must move to adopt integrating this information into remote sensing and epidemiological methodologies. While dengue is the world's most rapidly spreading mosquito-borne virus, a host of other viruses, Zika and Chikungunya among them are also on the doorstep.

CHAPTER 2: Movement of People from Sonora into Arizona

Abstract Autochthonous transmission of dengue in a region where the virus is non-endemic is dependent on the presence of a suitable habitat for *Aedes aegypti*, the presence of infected individuals who acquired the virus elsewhere, and local environmental conditions that enable *Aedes aegypti* to become a dengue-competent vector. Dengue is not endemic in Phoenix, AZ, but *Aedes aegypti* is abundant and there are locations within the city that have the potential to produce the necessary conditions to allow it to become capable of transmitting dengue, therefore the focus of this chapter is to try to determine areas within the Phoenix metropolitan area where dengue is mostly likely to be imported. A majority of dengue-infected persons entering Phoenix are Hispanic and Latino, with evidence indicating this is a result of city's proximity to hyper-endemic Sonora, MX and the high rates of travel across the Arizona/Mexico border. An outbreak in Sonora, therefore, can provide information that allows dengue surveillance in Phoenix to be more highly specified.

INTRODUCTION

In his book *Guns, Germs and Steel*, Jared Diamond writes extensively on the capacity of disease to shape human geography. Instances of near entire populations meeting their demise at the hands of foreign pathogens have often been at the epicenter of periods of great political and social shift throughout history, with the Bubonic Plague in 14th Century Europe and the annihilation of Native American populations during the colonization of the Americas being notable examples. Though thankfully not always on the same scale as these two instances, the process whereby pathogens spread during episodes of human population convergence has always been one of the side effects of human movement across the planet. Contemporary mass migration patterns from the Middle East into Europe and from Latin America into the United States fueled by either drought, violence, economic depression, or in some cases all three, has placed people from different cultures and regions of the globe directly next to one another, each in effect sharing their "germs" with the other. The dengue virus has seen massive spread over the last several decades thanks to global trade networks and an increased volume of air traffic, and is considered by the WHO to be the world's fastest spreading arthropod-born disease (WHO Dengue and Severe Dengue Factsheet, 2016).

While dengue is not yet endemic in Arizona, two sets of factors suggest the state is at risk. First, the prevalence of dengue in the neighboring Mexican state of Sonora and the volume of traffic between Sonora and Arizona, raises concern among public health organizations in the state of Arizona and the Centers for Disease Control and Prevention that the number of imported cases is likely to rise in the coming decades ("Arizona 2015 Dengue Statistics," 2015). That is, the number of people contracting dengue in Sonora combined with high volume of traffic across the border exposes Arizona to an increased risk of importing dengue. Second, one of the potential vectors of dengue, *Aedes aegypti*, is already present in urban areas in Arizona and changing microclimatic conditions in Arizona's cities increases the risk that it may become a competent vector for the dengue virus.

I assume that the most probable way in which dengue will enter the Phoenix metropolitan area will be through the blood of an infected individual, or individuals, traveling into the region. While it is possible for an infected mosquito to accompany some type of transport vehicle (e.g. car, train, bus, plain, etc.) traveling to Phoenix and bite someone on arrival, locally acquired dengue will more than likely be transmitted by local mosquito populations who have taken blood meals from people entering the city with the virus after acquiring it somewhere else. Epidemiological monitoring of dengue worldwide in conjunction with monitoring rates of travel into Phoenix from dengue-prone regions can provide insight into possible locations of origin should autochthonous dengue appear in Phoenix.

Dengue is endemic in 128 countries and can theoretically enter Arizona from any one of them. However, the volume of traffic between Sonora and Arizona, together with their proximity to one another, warrants close attention to risks from that source. While there are data on cross border travel, the movement of people once they have entered Arizona has to be inferred based on other factors, like the distribution of Hispanics and Latinos throughout the state. To further assess probable locations of dengue emergence, I consider the distribution of Hispanic and Latino populations in the urban areas where *Aedes aegypti* currently exists and is most likely to become a competent vector, focusing on Greater Metropolitan Phoenix. In Maricopa County, both the most populated county in the state and the location of Arizona's capital (Phoenix), individuals who identify as either Hispanic or Latino comprise roughly 1.18 million, or more than 25%, of the total population (U.S. Census, 2010). As with minorities elsewhere, they tend to locate in areas of the city populated by members of their own race and/or ethnicity (Bauer, 2005; Charles, 2003; Logan, 2002; Wen, 2009; Yancey, 1976). I assume that those who are entering Arizona from Sonora are likely to gravitate to one of these areas.

An outbreak of dengue in Sonora starting in September 2014 and culminating in December 2015, and an associated increase in cases of dengue reported in Arizona during this time (none of which were locally acquired), gives further evidence for an elevated risk of dengue emerging in Arizona due to its proximity to the Mexican border. San Luís Río Colorado, Sonora, Mexico borders Yuma County, Arizona to the south and is just 26 miles away from the City of Yuma (Population: 91,923) (Jones, 2016). During the 2014 outbreak, San Luís Río Colorado reported 52 cases of locally acquired dengue, and Yuma County reported 93 imported cases of dengue. According to public health records maintained by the Arizona Department of Health Services, the years 2007-2013 reported on average between 3 and 10 cases of dengue imported into Arizona annually (Jones, 2016). 2014 is characterized by an increase in imported cases 9 times greater than the previous seven years' average. In 2015 there were 24 cases of dengue imported into Arizona, number nearly 3 times previous years' averages, excluding 2014. In 2016, the number of imported cases presently sits at 14, mirroring decline in the number of infections across Sonora, which have fallen from 9,295 in 2015 to 5,244 so far in 2016 (Border Infectious Disease Surveillance Program 2015 and 2016).

An outbreak in 2005 in Brownsville, TX was likewise the result of elevated incidence of dengue in the adjacent border town of Matamoros, Tamaluipas, MX. Brownsville reported 25 cases of locally acquired dengue during this period, constituting the greatest number of cases of dengue acquired within U.S. borders in the contiguous United States since the decline of Aedes aegypti populations a half-century earlier until 2013, when 53 cases of dengue (26 locally acquired) were reported in Cameron, Hidalgo, and Willacy counties (all three of which border Tamaluipas in Texas) (Jones, 2016; Thomas 2013; Ramos, 2005). For these reasons, the CDC categorizes outbreaks on the northern border of Mexico as a major risk factor for dengue emergence in the U.S. (Jones, 2016). Arizona's status as a border state elevates this risk further.

This chapter examines the status of dengue in Sonora and the likelihood that an individual traveling across the border has dengue, and then seeks to use demographic information to complement the climatological assessments of high-risk areas in the Phoenix metropolitan area for potential dengue emergence outlined in Chapter 1. Because high incidence of dengue in San Luís Río Colorado resulted in adjacent Yuma County hosting the highest number of infected persons entering Arizona, border crossing data from Nogales, AZ (the largest port of entry nearest to Maricopa County) will be used to determine risk in the Phoenix metropolitan area. While this information is most relevant during dengue outbreaks in Sonora or in periods of above average transmission, it may also be used to inform routine vector control operations in the city. So long as the local destinations of visitors from other countries bears some relation to the distribution of the local population (so long as visitors map to kith and kin) this method may usefully inform both surveillance and vector control.

DATA AND METHODS

In order to determine the likelihood that travelers coming into Arizona from Sonora are (a) infected, and (b) that they may end up in the Phoenix metropolitan area, the method adopted herein was a threefold one. First, an account of dengue in Sonora describing incidence rates and numbers of infected individuals for at least the most recent year was used to determine incidence rate in the transient population moving from Sonora into Arizona. Incidence rates for the state of Sonora were applied to all persons located within its boundaries, regardless of citizenship or nationality. Because this assessment is only meant to be a first approximation, qualifying conditions intended to differentiate incidence rates in the permanent population of Sonora from the transient one (such as average ages of people traveling and average ages of people most frequently infected with dengue) were not included.

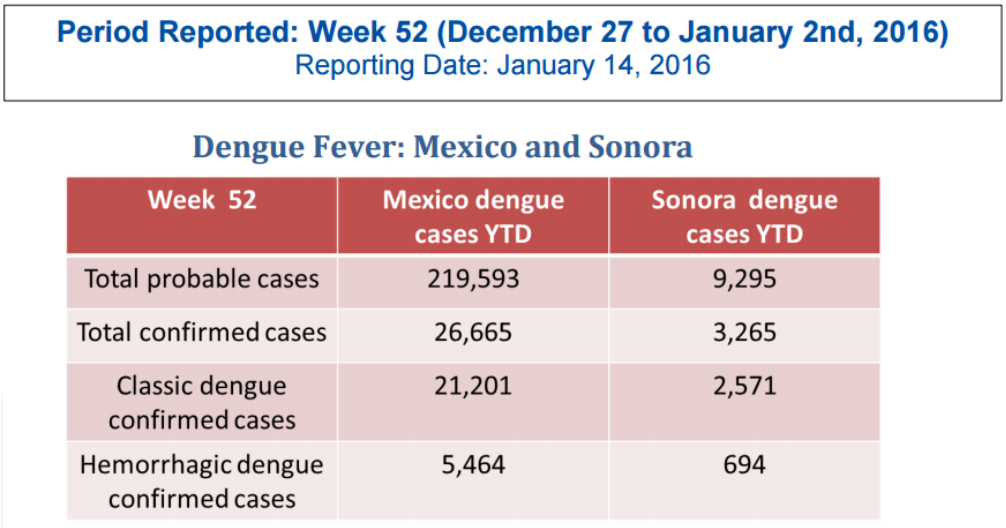
Second, even with this assessment being only a first approximation, restrictive parameters were applied with the intent of further specifying the number of people crossing the border who are likely to reach Maricopa County. The outbreak in Sonora in 2014 revealed that proximity to a border municipality experiencing high rates of dengue directly impacts where in Arizona the disease will show the greatest presence. Therefore, it was necessary to make assumptions regarding which types of travelers coming from Mexico were most likely to arrive in the Phoenix metropolitan area. Nogales has already been mentioned as the port of entry closest to Phoenix. Additionally, personal vehicle passengers were selected as the primary transient population examined in this paper for reasons expressed in the following sections.

Third, the spatial distribution of Hispanics and Latinos in Arizona and in Maricopa County was used (1) to determine what proportion of people crossing the border through Nogales end up in Maricopa County, and (2) to identify where in Maricopa County these individuals are likely to visit. This information was then combined with the micro-climatic data from Chapter 1 to prioritize areas in which to monitor mosquitoes for the dengue virus in the Phoenix metropolitan area.

ADHS 2015 Sonora Dengue Statistics and Cases of Dengue Imported into Arizona

Epidemiological data compiled by the Arizona Department of Health Services (ADHS) and the Mexican Ministry of Health were used as a source for incidence of dengue in Sonora. In 2015, the ADHS started to release weekly status reports for dengue in Sonora detailing information regarding numbers of new infections, percentage of infections resulting in dengue hemorrhagic fever (DHF), and year-to-date U.S.-Mexico border municipalities where dengue was reported. Numbers of new infections and cases of DHF in these reports were compared to national values (Mexico) for the same categories. Reports from the ADHS were used for all data from 2014 and later The Mexican Ministry of Health has dengue incidence organized by year dating back to 1984. Data from the Mexican Ministry of Health is used for years 2000-2013 to provide an understanding of the behavior of dengue in Sonora relative to the rest of Mexico.

Since the 2014 outbreak of dengue in Sonora, the ADHS has increased dengue monitoring and surveillance efforts, and it now produces weekly reports not only on the status of dengue, but other viruses transmitted by the *Aedes* family of mosquitoes as well. ADHS data used in this chapter covers up to epidemiological week 52 (full year) for 2015 (see Figure 2.1), and uses year to date (epidemiological week 39) information from 2016, for dengue monitoring in Sonora.



Period Reported: Week 52 (December 27 to January 2nd, 2016)
Reporting Date: January 14, 2016

Dengue Fever: Mexico and Sonora

Week 52	Mexico dengue cases YTD	Sonora dengue cases YTD
Total probable cases	219,593	9,295
Total confirmed cases	26,665	3,265
Classic dengue confirmed cases	21,201	2,571
Hemorrhagic dengue confirmed cases	5,464	694

Figure 2.1) Chart from ADHS weekly Sonora dengue report.

The ADHS was also used as a source for the number of dengue cases imported into Arizona each year. The number of cases imported into Arizona as reported by the ADHS covers the entire calendar year in 2015 and similarly up until epidemiological week 52 in 2016. Additional information provided on documents reporting cases imported into Arizona includes gender, race, ethnicity, age, travel history, and for several of the patients the viral serotype found in their blood. Probable cases of dengue, as opposed to confirmed cases, were used to make an assessment on the total number of imported cases. Prevalence among travelers was computed as $(n/N)*T$ where n is the number of cases in Sonora in 2015, N is the total population of Sonora, and T is the number of travelers across the U.S. – Mexico border through Nogales.

Bureau of Transportation Statistics U.S.- Mexico Border Crossing Information

Publically available data provided by the United States Bureau of Transportation Statistics (BTS) was used to determine the number of individuals crossing the border from Sonora into Arizona each month for the previous 15 years. People crossing via personal vehicle or as pedestrians significantly outnumbered those crossing by any other method of transportation (i.e. buses, trains). These were the only transportation types used to measure border traffic in this study. The number of crossings through the two largest ports of entry into Arizona, Nogales and San Luis (called San Luis Rio Colorado on the Mexican side of the border), was chosen as the most likely locations from which dengue-infected travelers will enter the Phoenix metropolitan area. Numbers of individuals crossing at other border sites along the Arizona-Sonora border are negligible relative to the total number of crossings through Nogales and San Luis.

Border crossing numbers were used in conjunction with ADHS data reporting dengue incidence in Sonora to determine what proportion of people entering Arizona from Sonora are likely to have been exposed to dengue and to provide rough estimates of the number of people entering Maricopa County from Sonora based on the proportion of Hispanics and Latinos in Maricopa County relative to the rest of Arizona.

US Census Data Reporting Distribution of Hispanics and Latinos in Arizona and in Maricopa County

Demographic information available through the United States Census Bureau was used to map the location of populations of ethnic Hispanics and Latinos in Arizona by county and by census block inside Maricopa County. Proportions of Hispanic and Latino populations in Arizona were then used to infer dispersal patterns of persons crossing the border into Arizona from Sonora. The proportion of Hispanics and Latinos in Maricopa County relative to the rest of the state was used to calculate the likelihood that individuals crossing would end up in the Phoenix metropolitan area. Phoenix’s status as a major metropolitan area and potential thoroughfare to other major metropolitan areas in the United States is neglected as a factor influencing the likelihood of individuals coming from Sonora to enter or stay in the city. The numbers also fail to incorporate undocumented immigrants entering Arizona and therefore also Maricopa County. They should be regarded as a first approximation only.

The distribution of Hispanics and Latinos inside Maricopa County and the Phoenix metropolitan area were likewise used as first approximation of the destinations of travelers from Sonora. This assumption enabled the narrowing down of locations in the city where an individual infected with dengue is most likely to be located given an outbreak in Sonora. Areas in the Phoenix metropolitan area with the highest proportion of

Hispanics and Latinos relative to other ethnicities were displayed on maps showing their locations in the city.

NDVI-DTR Maps Generated in Chapter 1 Used to Further Delineate Areas Susceptible to Dengue Emergence.

Map 1.3 shows locations at risk of dengue emergence for micro-climatic reasons. When coupled with the demographic distribution of Hispanic and Latino populations in Phoenix generated using Census data it indicates areas where *Aedes aegypti* might encounter an infected person following an outbreak in Sonora. Because census block data is not as highly specified as the NDVI data used in this project, the Census blocks were converted into raster format and broken down into 30x30 meter pixels. The Hispanic and Latino population data in raster format appear the same as they do when they are polygons, except they are broken down into much smaller parts wherein each pixel in the Census block has the same value. Information revealed on the maps therefore is on the scale of the NDVI map (30x30 meters). A final map displays the parts of the city where high densities of Hispanics and Latinos coincide with areas in which DTR is a minimum.

RESULTS

Dengue in Sonora

According to the Mexican Ministry of Health, cumulative incidence rate of dengue in Sonora between 2000 and 2013 was 391.1 (per 100,000), compared to the national incidence rate of 436.9 over the same period of time (Anuarios de Morbilidad, 2016). Though with incidence rates often lower than what are experienced nationally, Sonora has consistently reported similar patterns of dengue infection to those experienced by other Mexican coastal states (central states often lack sufficient moisture and are typically higher in elevation than where dengue would be expected to be most prevalent) (See Table 1.1). Elevated case numbers in the south of Mexico, therefore, might indicate a potential increase in cases in Sonora.

Year	Approximate Dengue Incidence -Sonora (per 100,000)	Approximate Dengue Incidence - Mexico (per 100,000)
2000	15	1
2001	0	5
2002	14	12
2003	45	6
2004	2	7
2005	3	18
2006	4	24
2007	0	43
2008	42	29
2009	19	101
2010	165	39
2011	4	17
2012	52	65
2013	55	88

Table 2.1) Comparison between dengue incidence rates in Sonora and the national incidence rates in Mexico from 200-2013. (Data from the Mexican Ministry of Health)

A total of 9,295 cases of dengue were indicated as being probable by the ADHS in Sonora by the end of 2015 (see Figure 2.1), amounting to 5% of the total incidence of dengue infection in Mexico. Cases of dengue hemorrhagic fever (DHF) in Sonora in the same year accounted for 26% of the total number of infections in the state, a proportion significantly higher than the 11% seen in the rest of Mexico. Multiple strains of dengue circulate in Sonora, including the highly virulent DENV-2 strain, which may in part explain the elevated incidence of DHF in Sonora relative to the rest of the country. In

2015, infection rates began to climb in epidemiological week 23 (beginning of May) and skyrocketed in week 37 (mid-August). Infections continued to rise at a sustained rate until week 45 (mid-October), where they leveled out. An additional spike in cases of dengue occurred in the last few weeks of 2015 (See Figure 2.3). During the period of highest transmission, at least six municipalities in Sonora that border Arizona were reported as having dengue (See Figure 2.2).

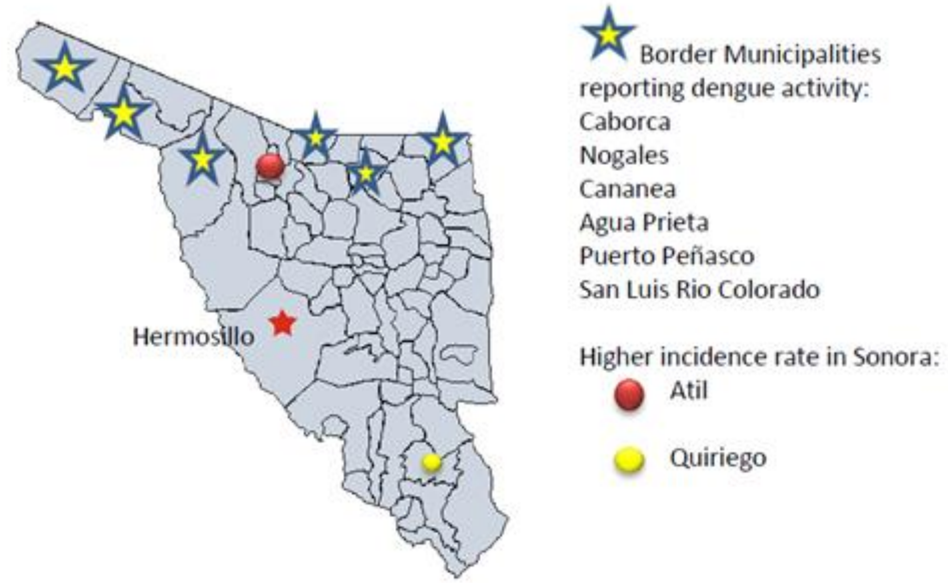


Figure 2.2) Border Municipalities in Sonora, MX with reported incidence of dengue. (Image produced by the Arizona Department of Health Services)

2015 confirmed Cases of Dengue in Sonora

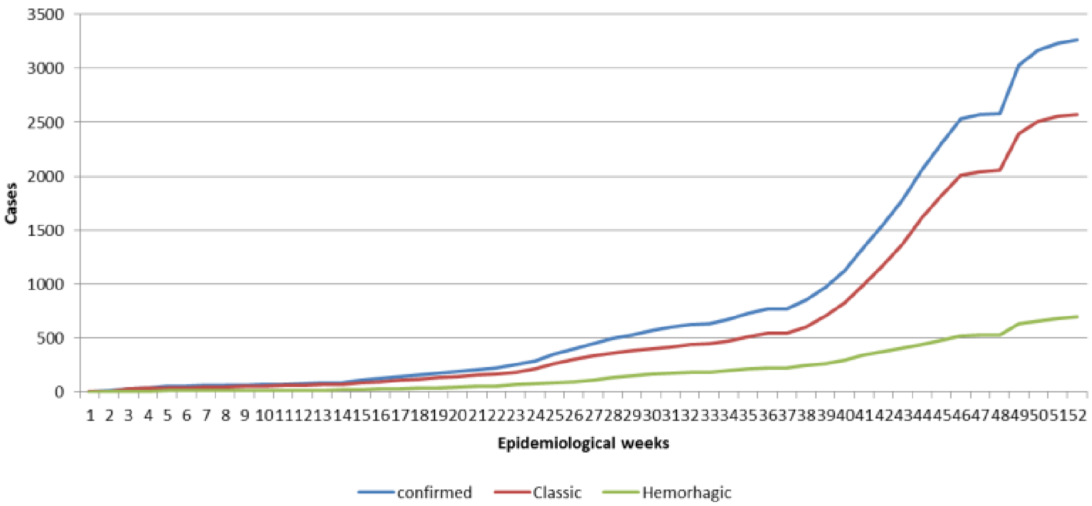


Figure 2.3) 2015 cases of confirmed dengue by epidemiological week in Sonora, MX. This graph does not include probable cases, but the trend indicated would be the same. (Graph produced by the Arizona Department of Health Services)

Over the course of 2015, 24 cases of dengue were imported into Arizona, 14 of which were known to have originated from outside of the United States, 1 came from within U.S. borders and 7 were documented as unknown. In an interview with an Arizona Department of Health Services official it was clarified that, despite being officially recorded as unknown, those 7 cases also originated outside of the United States. Volume of traffic across the Arizona-Mexico border tends to decline in the summer months (July, August, September), corresponding with the time of year that Sonora begins to experience its higher rates of infection. Incidence rate for dengue in Sonora by the end of 2015 was 111.33, a number 5 times the national incidence rate of 22.04.

The number of probable infections in Sonora during each month as reported by the ADHS and the total population of Sonora (2.66 million) were used to calculate the incidence rate of dengue in Sonora for each month of the year using as a formula $IR=(I_b-$

$I_a) / (P/100{,}000)$, where IR is the incidence rate, I_b is the number of total infections in Sonora at the end of one month, I_a is the total number of infections in Sonora at the end of the month before I_b (so I_b-I_a is the number of new cases each month), P is the total population of Sonora, and *100,000* is the unit of measure by person for incidence rate.

Incidence rates remain low until June, when rates begin to pick up slightly, wherein they remain consistent throughout July. Rates show a rapid increase beginning in August and culminating at 93.98 in October. By the end of December rates have again declined (See Figure 2.4). Values acquired for each month are used in Table 2.2 to determine probable numbers of infected individuals crossing the border through Nogales via passenger vehicles throughout 2015.

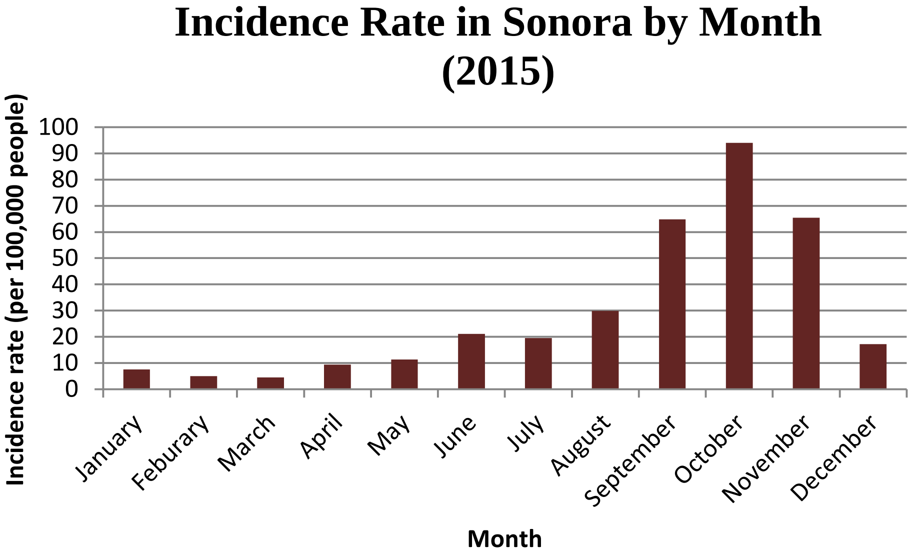


Figure 2.4) Incidence rates of dengue in Sonora each month for 2015 based on numbers of new infections accumulated each month. (Data from the ADHS was used to create this graph)

Border Crossings

Over the last 15 years, an average of 13 million people traveled from Sonora to Arizona through the Nogales port of entry, 8 million travelling in personal vehicles and 5 million travelling as pedestrians. 8 million more entered through San Luis, 5.5 million of which were in personal vehicles and the remaining 2.5 million on foot. Following the economic recession in the United States, the number of annual crossings from Sonora into Arizona through Nogales decreased significantly, reaching a low of 8.8 million in 2011. The year with lowest reported crossings in San Luis (6.3 million) similarly occurred after the recession, but in 2010. In each, the annual number of travelers has since been increasing at rates similar to before the economic downturn. Total annual numbers of travelers through Nogales have still not recovered to pre-recession figures (See Figure 2.5).

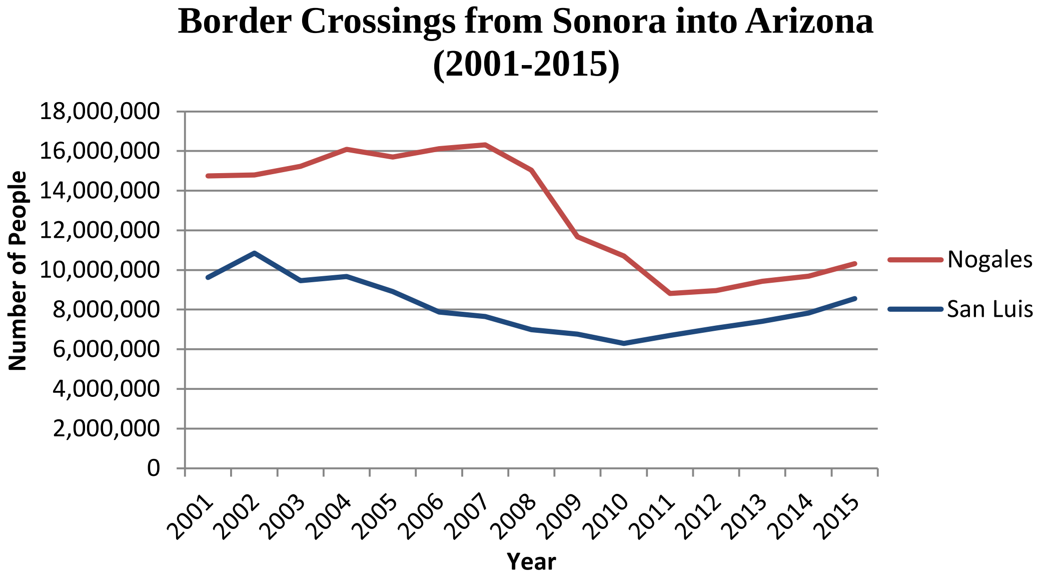


Figure 2.5) Annual number of border crossings from Sonora into Arizona through the Nogales and San Luis ports of entry (2001-2015). (Data from the United States Department of Transportation)

As I have already remarked, the destinations of persons entering into Arizona from Sonora are unknown, as is the length of time they spend in the state. This makes it difficult to say what percentage of people coming through Nogales and San Luis are entering and/or staying in Phoenix. All that is known is the distribution of Hispanics and Latinos in Arizona recorded at each census. The propensity of visitors to concentrate in areas where they have kith and kin, however, allows us to make assumptions about the distribution of those individuals who do cross the border from Sonora into Arizona (See following sections).

Method of transportation likewise helps inform the likelihood that an individual crossing the border in Nogales or San Luis will end up in Phoenix. Although it cannot be statistically demonstrated using the data gathered for this report, I assume that persons traveling across the border as pedestrians have a greater likelihood of staying in the port of entry border town than those who enter in passenger vehicles. Passenger vehicles, therefore, were selected as being more likely to transport an infected person into the Phoenix metropolitan area (See Figure 2.6). Monthly passenger vehicle crossings (number of people inside each passenger vehicle) from each port of entry where used for calculations aimed at determining the probable number of infected individuals entering the state (See Table 2.2) and then again for entering Maricopa County (See Table 2.3).

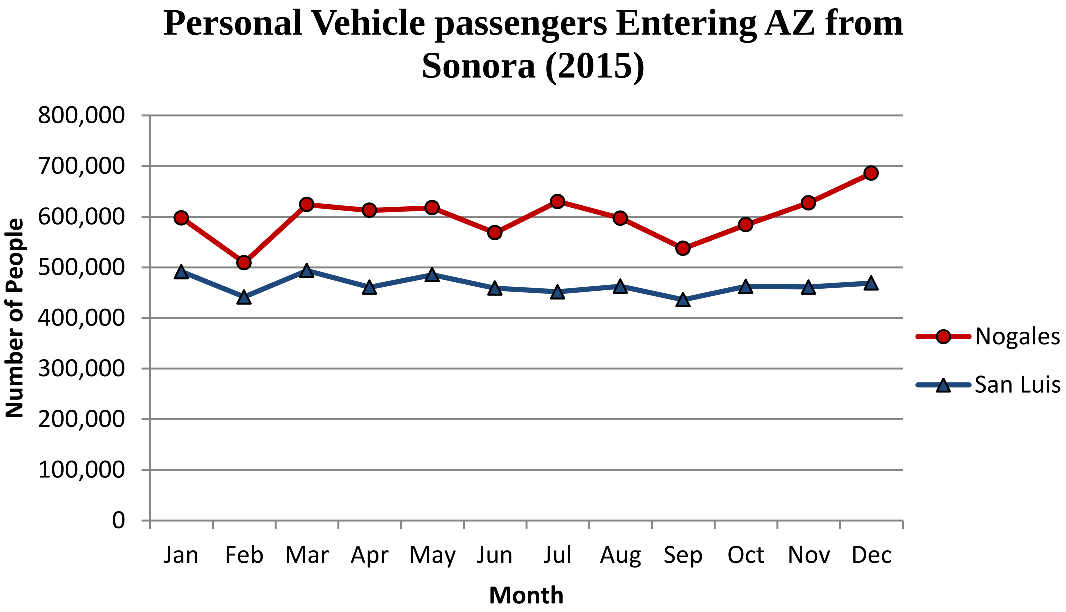


Figure 2.6) Monthly passenger vehicle border crossings into Arizona through the Nogales and San Luis ports of entry in 2015. A year-end total was 12.8 million people crossing.

Month	Number of Passenger Vehicle Entries	Sonora Dengue Incidence	Number of Potentially Infected Persons Entering Arizona*
January	1,088,967	7.52	82
February	950,590	4.89	46
March	1,117,732	4.51	50
April	1,073,281	9.40	101
May	1,103,015	11.28	124
June	1,027,031	21.05	216
July	1,081,798	19.55	211
August	1,059,956	29.89	316

September	973,642	64.85	631
October	1,046,385	93.98	983
November	1,088,295	65.38	712
December	1,154,611	17.14	198

Table 2.2) Number of probable persons entering Arizona from Sonora through the Nogales and San Luis ports of entry each month who are infected with dengue based on the incidence rate of dengue in Sonora in each month in 2015 (See Figure 2.3). *Actual numbers of reported cases of imported dengue are significantly lower than those predicted using dengue incidence of Sonora. While it is likely that the values in this chart for infected persons crossing the border are high, their considerable divergence from reported values raise questions regarding efficiency of reporting effort and dengue monitoring in Arizona.

Distribution of Hispanic and Latino Population in Arizona

Using U.S. Census data describing the distribution of Hispanics and Latinos in Arizona by county, I infer the proportion of individuals entering Arizona from Mexico who will potentially end up in Maricopa County. Because Maricopa County is home to close to 60% of the state's Hispanic and Latino population, and based on the propensity of ethnic minorities to distribute themselves according to established ethnic enclaves when traveling or resettling, I assume that a comparable proportion of those crossing the border from Sonora through Nogales and San Luis will likewise enter Maricopa County. It is possible that the proximity of Nogales to Maricopa County will increase the likelihood that people crossing into Arizona through that port of entry will enter Maricopa County, as was demonstrated in Yuma County in 2014, however no data showing the distribution of people entering the state based on their selected port of entry was used in this report. Keeping this in mind, I continue to infer that of the 12.7 million people crossing into Arizona through both Nogales and San Luis last year in passenger vehicles, about 60% of them, or 7.7 million, were entering Maricopa County.

In the months where dengue incidence is the highest in Sonora (September, October, and November) there were passenger vehicle crossings into Arizona equaling around 970,000 – 1,100,000 people per month (the number of people per month increased each month), so I assume that somewhere between 582,000 and 660,000 of them were inside Maricopa County at some point (See Tables 2.2 and 2.3). Using probable dengue incidence rates for Sonora in 2015 reported by the Arizona Health Department of Health Services (Figure 2.3 and Table 2.3), between 375 and 600 infected individuals can be inferred as being inside Maricopa County in each of these months.

Length of stay cannot be inferred from this data, but given the centrality of Phoenix in the state and its potential as a thoroughfare between other major metropolitan centers in the U.S., this estimation, while rough, can be considered useful in this context. Moreover, an extensive layover in Phoenix would not necessarily be required for the transmission of dengue, as all that is necessary is for one infected individual to come in contact with a mosquito capable of transmitting the virus. Viral load substantially declines after 2 weeks, as does a person's risk for passing the virus alone.

County	**Hispanic and Latino Population**	**Non-Hispanic and Latino Population**	**Total Population**	**Percent Hispanic and Latino Within County**	**Percent of Arizona Hispanic Population**
Maricopa	1,128,741	2,688,376	3,817,117	29.57	59.56
Pima	338,802	641,461	980,263	34.56	17.88

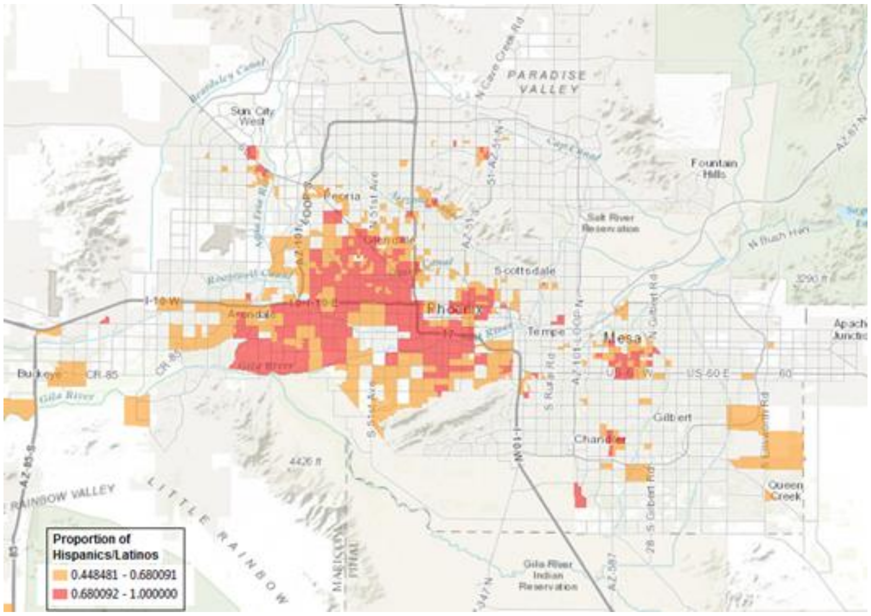
Pinal	106,977	268,793	375,770	28.47	5.64
Yavapai	28,728	182,305	211,033	13.61	1.52
Mohave	29,569	170,617	200,186	14.77	1.56
Yuma	116,912	78,839	195,751	59.72	6.17
Coconino	18,166	116,255	134,421	13.51	0.96
Cochise	42,543	88,803	131,346	32.39	2.24
Navajo	11,571	95,878	107,449	10.77	0.61
Apache	4,113	67,405	71,518	5.75	0.22
Gila	9,588	44,009	53,597	17.89	0.51
Santa Cruz	39,273	8,147	47,420	82.82	2.07
Graham	11,320	25,900	37,220	30.41	0.60
La Paz	4,806	15,683	20,489	23.46	0.25
Greenlee	4,040	4,397	8,437	47.88	0.21
TOTAL (Arizona)	1,895,149	4,496,868	6,392,017	29.65	100

Table 2.3) Total number of Hispanics and Latinos in each county in Arizona, their percentage in each county, and each county's percentage of Hispanics and Latinos in relation to the entire state.

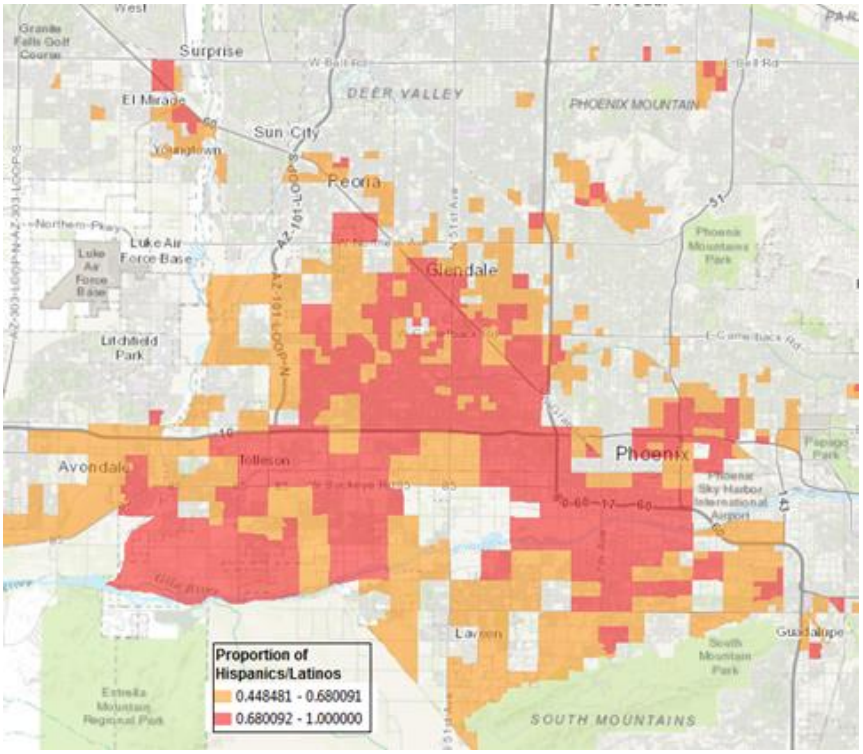
Citywide Distribution of Hispanic and Latino Population in the Phoenix Metropolitan Area

The distribution of Hispanics and Latinos across the Phoenix metropolitan area follows patterns of ethnic and racial minority grouping found in other large metropolitan regions across the country (Bauer, 2005; Charles, 2003; Logan, 2002; Wen, 2009).

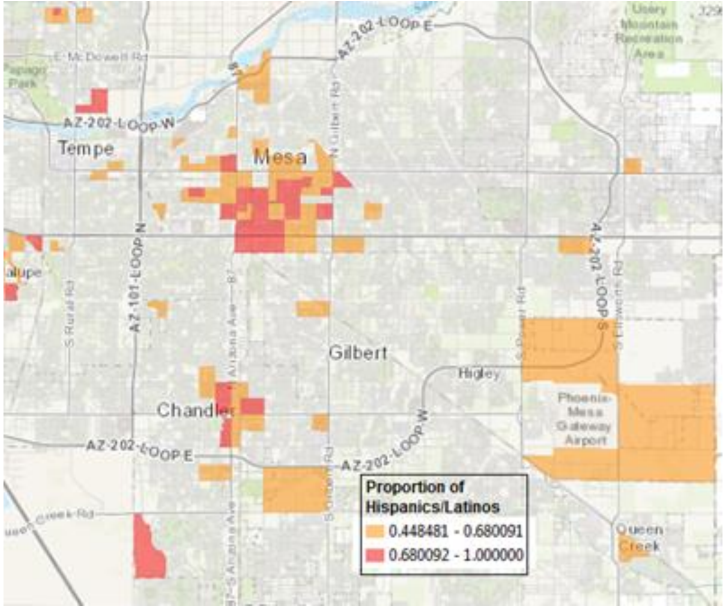
Hispanics and Latinos account for nearly a third of the total population in the city. They are not distributed evenly across the metropolitan region, but occur in distinct groupings in South and Southwest Phoenix, South Glendale, Avondale and Tolleson, the area known as the Gateway District (near Phoenix Sky Harbor International Airport), El Mirage, Downtown Mesa, Downtown Chandler, and a small neighborhood just north of Tempe Town Lake near Highway 202 and Scottsdale Road. The population of these areas comprises a minimum of 45% Hispanics and Latinos, and in some cases more than 70% of the local population. The largest contiguous grouping of Hispanics and Latinos is comprised of an area that includes South and Southwest Phoenix, South Glendale, Avondale and Tolleson, and the Gateway District.



Map 2.1.1) Distribution of Hispanic and Latino population across the Phoenix metropolitan area. (Map generated using data from the U.S. Census Bureau)



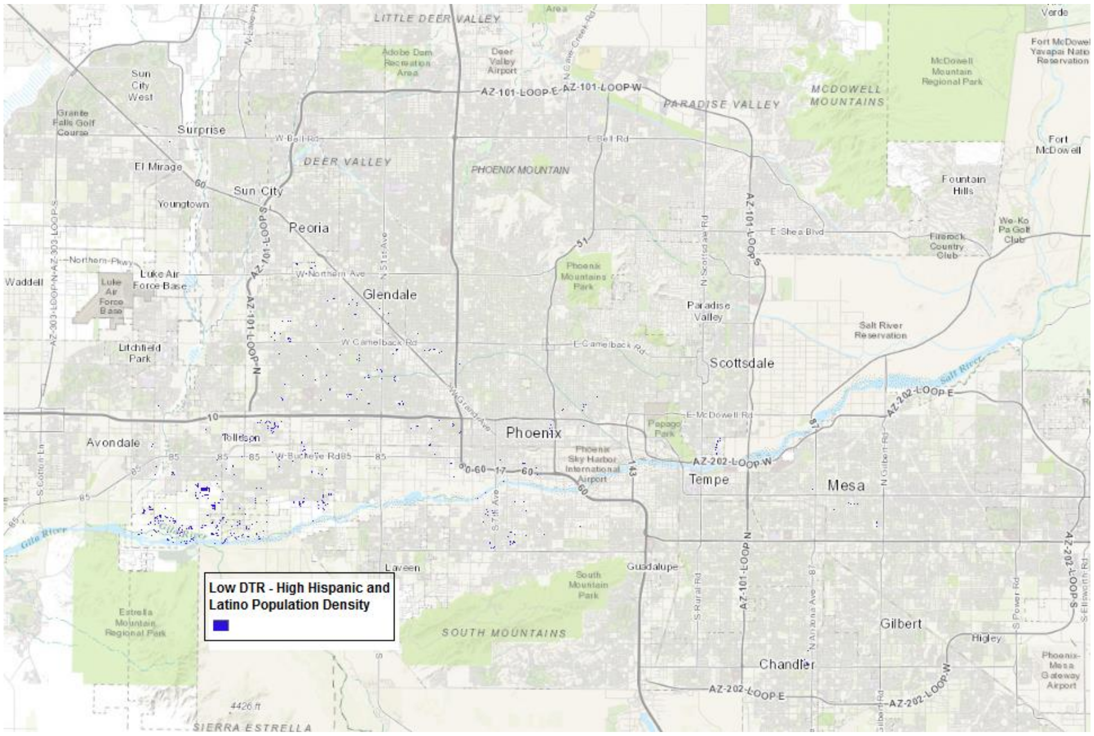
Map 2.1.2) Distribution of Hispanic and Latino population in South and Southwest Phoenix, South Glendale, Avondale and Tolleson, and the Gateway District. (Map generated using data from the U.S. Census Bureau)



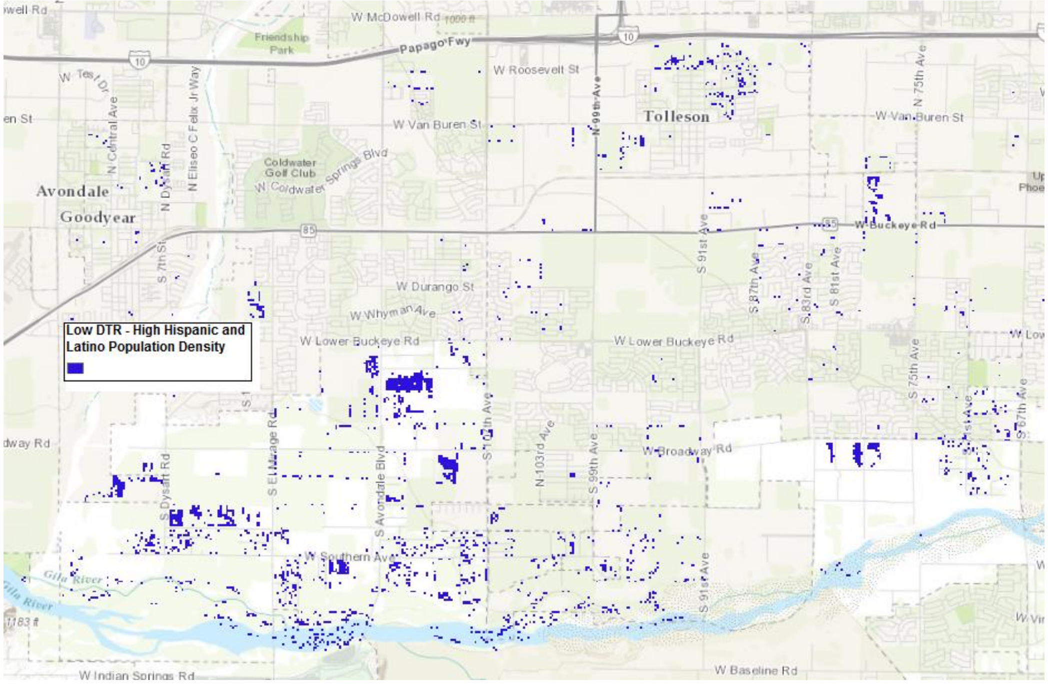
Map 2.1.3) Distribution of Hispanic and Latino population in Downtown Mesa and Downtown Chandler. (Map generated using data from the U.S. Census Bureau)

Overlay of Low DTR Locations in Metropolitan Phoenix and Areas of Highest Hispanic and Latino Density

To identify the implications of travel from Sonora for dengue risks, maps generated in **Chapter 1** detailing the locations in metropolitan Phoenix that are most likely to produce the conditions necessary for the transmission of dengue, based on information stating that transmission increases as diurnal temperature range (DTR) decreases, were overlaid on the demographic maps indicating areas of highest Hispanic and Latino population density. These maps provide a first approximation of the areas in which dengue is most likely to be transmitted by Aedes aegypti (see Chapter 1, *Showing a Relationship between mosquito abundance and NDVI*). That is, they indicate areas with environmental conditions likely to enable dengue transmission, and likely to be visited by an infected individual entering Maricopa through Nogales. The combined maps of environmental conditions, Hispanic and Latino density, and mosquito abundance are reported in Maps 2.4 and 2.5. Map 2.5 zoomed in to an area in the city that meets the 3 requisites for dengue transmission.



Map 2.2.1) Areas in Map 1.3 showing low DTR are overlaid here with areas where Hispanic and Latino populations meet or exceed 70% of the total population. NDVI pixels that were reclassified in Map 1.3 to show low DTR are shown here in blue if the demographic parameters are met. Low DTR areas that fall outside of these demographic parameters are not highlighted.



Map 2.2.2) Zoomed in Map 2.2.1. Areas highlighted here in blue meet both the micro-climatic and demographic parameters of this assessment. The area depicted in the map is Tolleson and Avondale, near the Gila River.

DISCUSSION

Vector control efforts in Maricopa County typically follow patterns of mosquito abundance, regardless of species type. Areas where trap yield is highest or where citizen reports of mosquitos are most frequent receive preferential treatment. Mitigation strategies include neighborhood-scale fogging, treatment of standing water bodies with larvicides (typically temephos), and educating local populations on breeding habits of mosquitoes so that creating breeding conditions can be avoided. Different mosquito species respond differently to each treatment, for instance mosquito populations of the *Culex* family, most notable in Arizona for transmitting West Nile and St. Louis encephalitis, decline significantly following neighborhood-scale fogging efforts and treatment of standing water bodies with larvicides.

Behavior patterns and genetic composition of *Aedes aegypti*, however, limit the effectiveness of fogging on nearly all scales. Because *Aedes aegypti* is most active during the day, and vector control fogging is only permissible late at night, insecticides dispersed using this method fail to reach *Aedes aegypti* mosquitoes where they sleep and are therefore rarely effective. The tendency of *Aedes aegypti* to complete its lifecycle near homes and other buildings likewise limits vector control's ability to effectively use neighborhood-scale fogging methods to target mosquito populations. According to Maricopa County Vector Control, *Aedes aegypti* in Arizona also exhibits genetic resistance in excess of 80% for the insecticides permissible for use in the United States (many experts believe the global rebound in *Aedes aegypti* was enabled by the large-scale banning of DDT).

The most effective methods for *Aedes aegypti* mitigation in Latin America and Southeast Asia, where the mosquito is most abundant, have always been educating the population on how to prevent mosquito populations from breeding in or near their residences. Governments where power is centrally located, such as Cuba and Singapore, have historically been the most successful at using these strategies. Enforcement of penalties for citizens allowing *Aedes aegypti* mosquitoes to breed on their property incentivized small-scale mosquito control efforts. Education initiatives for the population of Arizona on limiting breeding space for *Aedes aegypti* were invigorated following the 2014 dengue outbreak in Sonora, but little incentive to comply with these recommendations in Arizona further reduces Maricopa County Vector Control’s ability to mitigate *Aedes aegypti* populations.

Remote sensing methods are only used infrequently by vector control agencies except in instances where mean temperature predictions indicate a potential increase in mosquito populations. However, periods of the year where mean temperatures are most conducive to *Aedes aegypti* population increase are relatively consistent and therefore repeated use of remote sensing techniques that convey this information are often unnecessary barring unusual climate patterns (for instance years marked by the El Niño Southern Oscillation). *Aedes aegypti* in Maricopa County, moreover, has shown its ability to persist during the hottest period of the year, between June and July, and MCVC reports sporadic increases of abundance during these months when temperatures are conventionally thought to be too extreme for the survival of *Aedes aegypti* (temperatures in Phoenix often exceed 45˚C in the summer while literature values for maximum survival temperature for *Aedes aegypti* are normally limited to 35˚C). *Aedes aegypti*'s preference for vegetated areas adjacent to buildings, which are presumably being cooled during these months, may in part explain this phenomenon.

Reports monitoring the status of dengue submitted weekly by the Arizona Department of Health Services Office of Border Health are employed by public health officials across the state to inform medical professionals regarding the potential for an increased number of patients exhibiting symptoms of dengue and the proper diagnostic protocol, but estimating potential numbers of imported cases offers, as this study has shown, are only rough estimates. Maricopa County Vector Control faces political pressure to continue to use mosquito mitigation strategies that have proven largely ineffective for *Aedes aegypti* (Even if mitigation efforts are fruitless, the failure of a public health agency to appear to the general public as though it were making a substantive effort has political consequences. Developing countries that lack the resources or organizational capacity to effectively mitigate *Aedes aegypti* populations are often reliant on this strategy to avoid social unrest).

Therefore, in the event of an outbreak of dengue in Sonora, Mexico, this study suggests that additional fine scale data on micro-climatic conditions and travel patterns might be helpful in informing efforts on mosquito control and epidemiological monitoring. In conjunction with information delimiting locations in the Phoenix metropolitan area most likely to produce environmental conditions enabling dengue transmission, this chapter considers the role of passenger movements in changing the likelihood of a competent vector taking an infected blood meal. While here the example of Sonora is used as the probable origin from which dengue will enter the Phoenix metropolitan area, the same method for determining locations of emergence using demographic information could be applied to any source of visitors.

Based on the prevalence of dengue in Sonora, the volume of traffic across the Arizona-Mexico border, and the characteristics of the biophysical and social environment in Phoenix, I suggest areas where the likelihood that autochthonous transmission of dengue in the Phoenix metropolitan area is highest. It is worth adding that, because the population under examination in this chapter follows a distribution in the city that frequently places it outside of heavily vegetated regions (which have been described as producing the low DTR values that enable *Aedes aegypti* to become a competent dengue vector), the locations where environmental conditions favorable for dengue transmission can be found to exist primarily outside of areas inhabited predominantly by Hispanics and Latinos. This limits the locations in Phoenix most at risk for dengue emergence to those in Map 2.4, and is one possible explanation for why there has been no autochthonous dengue in Phoenix to date.

This similarly reduces the regions in the city that require the greatest degree of attention in mosquito control and epidemiological monitoring. Control of *Aedes aegypti* in these places (Map 2.4) may have a larger impact on disease risk than mosquito control elsewhere. The areas indicated on Map 2.4 would also be a reasonable location for surveillance should it be determined that the virus has been acquired by someone locally.

The locations indicated in Chapter 1 in Map 1.3 as producing the greatest environmental risk for transmitting dengue that exist outside of the predominantly Hispanic and Latino neighborhoods would be categorized by this study as being the areas of next highest risk. This assessment takes into account the movement of people throughout the city, and recognizes that, while someone entering Arizona from Sonora may live in the areas indicated by Map 2.1, their work may take them elsewhere in the city and may include the regions highlighted in Map 1.3. In Maricopa County, the 2010 Census indicated that 61% of Labor and Helper jobs were held by the Hispanic and Latino population. These jobs include construction and landscaping, both of which potentially place individuals outside during the daytime when *Aedes aegypti* happens to be most active. While xeri-scaping is popular in Phoenix, it is arguably the more heavily vegetated regions in the city that require the most landscaping; and they are incidentally outlined by Map 1.3 as being the environments in the Phoenix metropolitan area most at risk for producing climatic conditions that enable dengue transmission. This risk is not included on the maps provided here, as determining the probable locations of people whose jobs sites are always shifting was not something achievable with available data.

Recognizing that the approach adopted here is potentially provocative, given the political climate in Arizona surrounding the border and immigration, it is worth emphasizing that this paper is in no way designed to be prejudicial. It contributes to a large body of research describing human migration patterns and the associated spread of disease, and seeks only to exploit all available information to improve the understanding of risk.

Furthermore, this is very much a first approximation. The calculations used to determine numbers of potentially infected persons entering Arizona from Sonora produce numbers several times what is actually recorded. While someone can be infected with dengue and not display symptoms, and can therefore in theory be able to escape epidemiological monitoring while at the same time be capable of transmitting the virus to a mosquito, and while reporting efforts for dengue in Arizona could be improved, these still do not explain the 575 person difference in potentially imported cases from Sonora and cases actually reported in Arizona. Even though the model was not intended to produce precise results, and was only used get a sense of what proportion of infected people entering Arizona are likely to end up in the Phoenix metropolitan is, the difference between calculated imported cases and reported cases indicates something about movement of people from Sonora into Arizona that the model fails to capture.

The conclusions drawn from this research do, however, highlight the capacity for disease surveillance techniques based on climate to be coupled with regional demographic analysis so that areas of likely disease emergence can be more clearly delineated and subsequently addressed prior to any actual illness. Public health agencies and vector control offices might consider using micro-climatic data to assist the control, not only *Aedes aegypti*, but other mosquito species known for transmitting diseases, and even other non-mosquito arthropods. Finally, this information calls for more accurate range prediction for dengue than models predominantly predicated on macro-climates. With one of the largest mass migrations in modern history presently unfolding, disease boundaries are assuredly in flux. If public health agencies in regions with high a inflow of migrants fail to make preparations for any diseases that might emerge as a result of the change in demographics, then the social consequences have the potential to be severe.

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APPENDIX A

FULL YEAR (MARCH 2013 – AUGUST 2014) DTR AVERAGE REGRESSIONS WITH NDVI

1 NDVI Pixel

Model Summary and Parameter Estimates

Dependent Variable: DTR

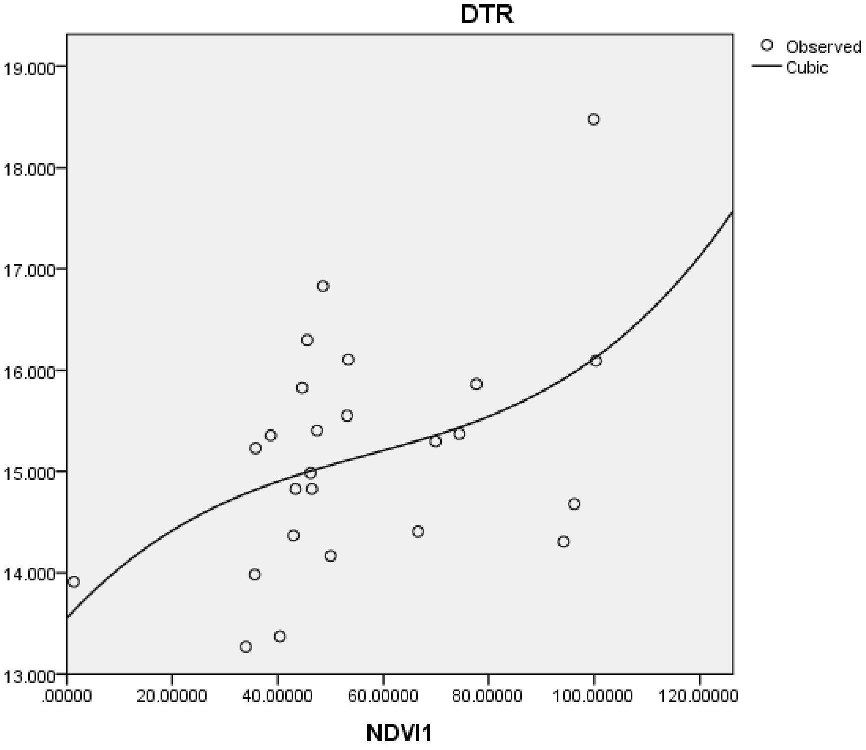
Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	
Cubic	.206	1.819	3	21	.175	13.555	.056	-.001	

Model Summary and Parameter Estimates

Dependent Variable: DTR

Equation	Parameter Estimates
	b3
Cubic	4.275E-6

The independent variable is NDVI1.



9 NDVI Pixels

Model Summary and Parameter Estimates

Dependent Variable: DTR

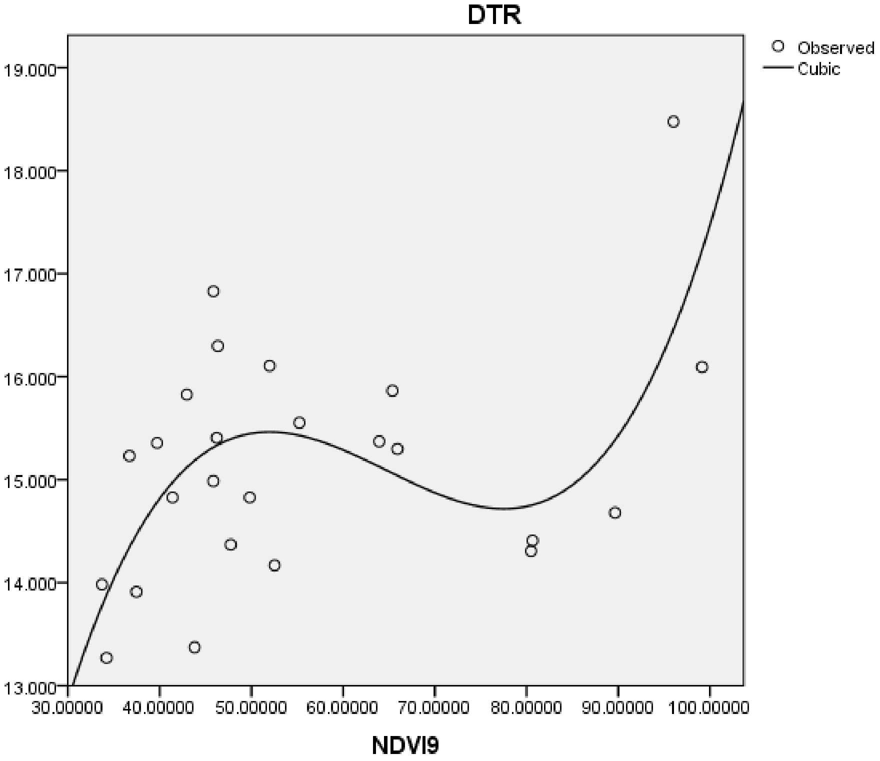
Equation	Model Summary					Parameter Estimates		
	R Square	F	df1	df2	Sig.	Constant	b1	b2
Cubic	.377	4.239	3	21	.017	-6.361	1.082	-.017

Model Summary and Parameter Estimates

Dependent Variable: DTR

Equation	Parameter Estimates
	b3
Cubic	8.952E-5

The independent variable is NDVI9.



25 NDVI Pixels

Model Summary and Parameter Estimates

Dependent Variable: DTR

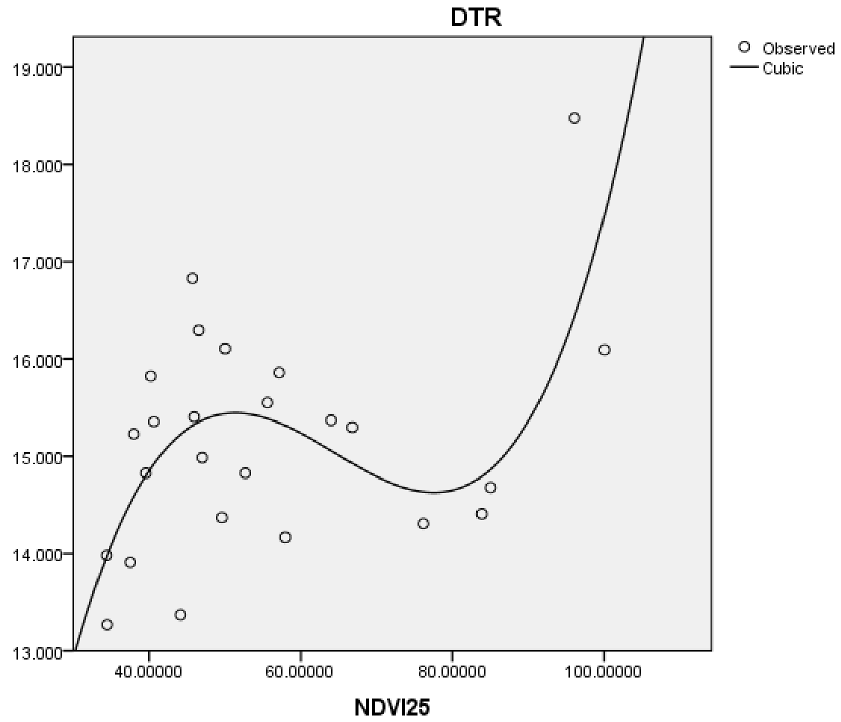
Equation	Model Summary					Parameter Estimates		
	R Square	F	df1	df2	Sig.	Constant	b1	b2
Cubic	.381	4.312	3	21	.016	-6.323	1.088	-.018

Model Summary and Parameter Estimates

Dependent Variable: DTR

Equation	Parameter Estimates
	b3
Cubic	9.106E-5

The independent variable is NDVI25.



49 NDVI Pixels

Model Summary and Parameter Estimates

Dependent Variable: DTR

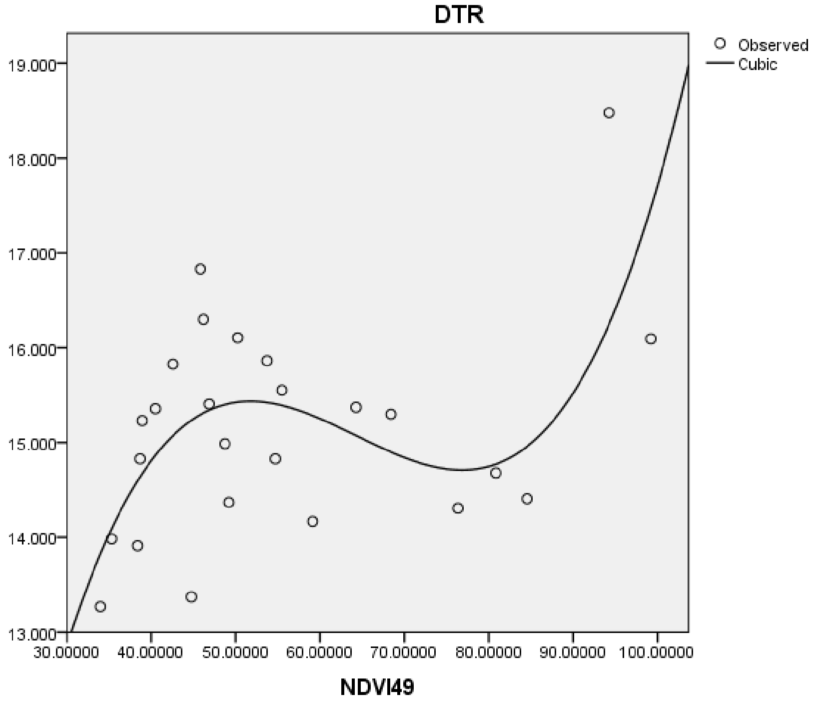
Equation	Model Summary					Parameter Estimates		
	R Square	F	df1	df2	Sig.	Constant	b1	b2
Cubic	.363	3.990	3	21	.021	-6.534	1.095	-.018

Model Summary and Parameter Estimates

Dependent Variable: DTR

Equation	Parameter Estimates
	b3
Cubic	9.182E-5

The independent variable is NDVI49.



81 NDVI Pixels

Model Summary and Parameter Estimates

Dependent Variable: DTR

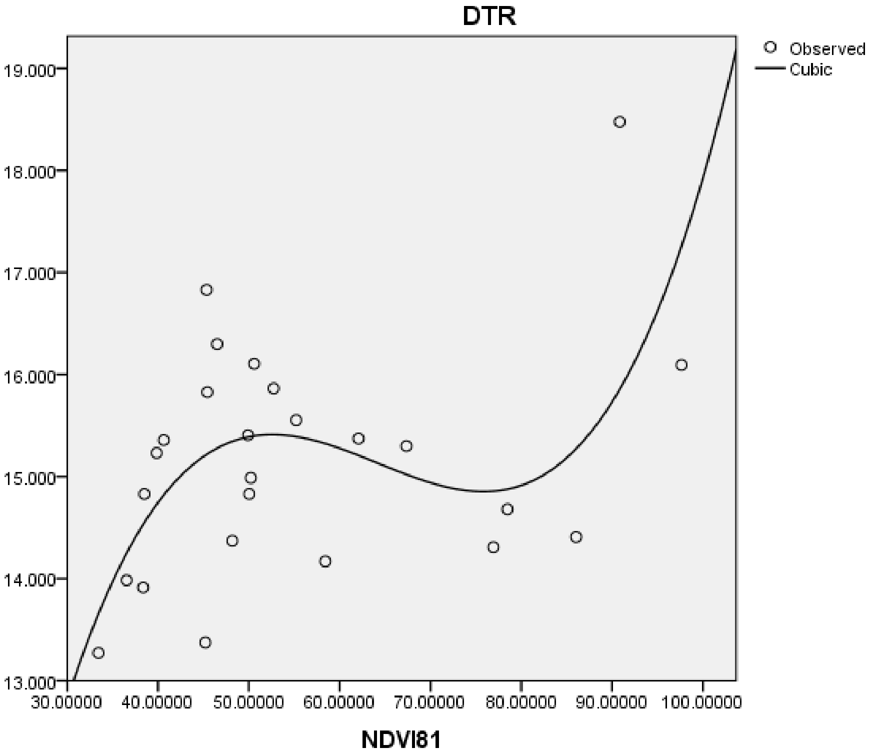
Equation	Model Summary					Parameter Estimates		
	R Square	F	df1	df2	Sig.	Constant	b1	b2
Cubic	.311	3.153	3	21	.046	-6.075	1.063	-.017

Model Summary and Parameter Estimates

Dependent Variable: DTR

Equation	Parameter Estimates
	b3
Cubic	8.895E-5

The independent variable is NDVI81.



121 NDVI Pixels

Model Summary and Parameter Estimates

Dependent Variable: DTR

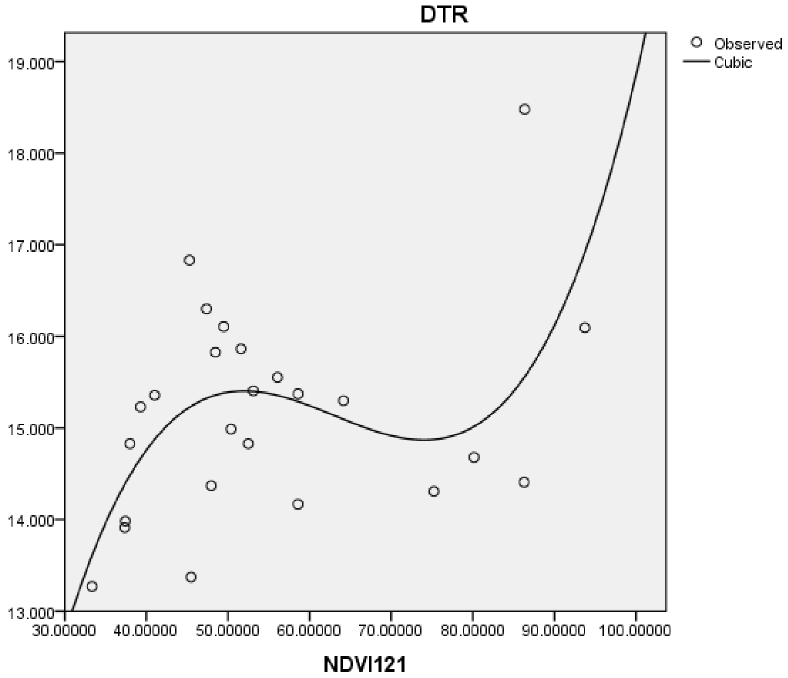
Equation	Model Summary					Parameter Estimates		
	R Square	F	df1	df2	Sig.	Constant	b1	b2
Cubic	.268	2.560	3	21	.082	-7.563	1.154	-.019

Model Summary and Parameter Estimates

Dependent Variable: DTR

Equation	Parameter Estimates
	b3
Cubic	9.995E-5

The independent variable is NDVI121.



169 NDVI Pixels

Model Summary and Parameter Estimates

Dependent Variable: DTR

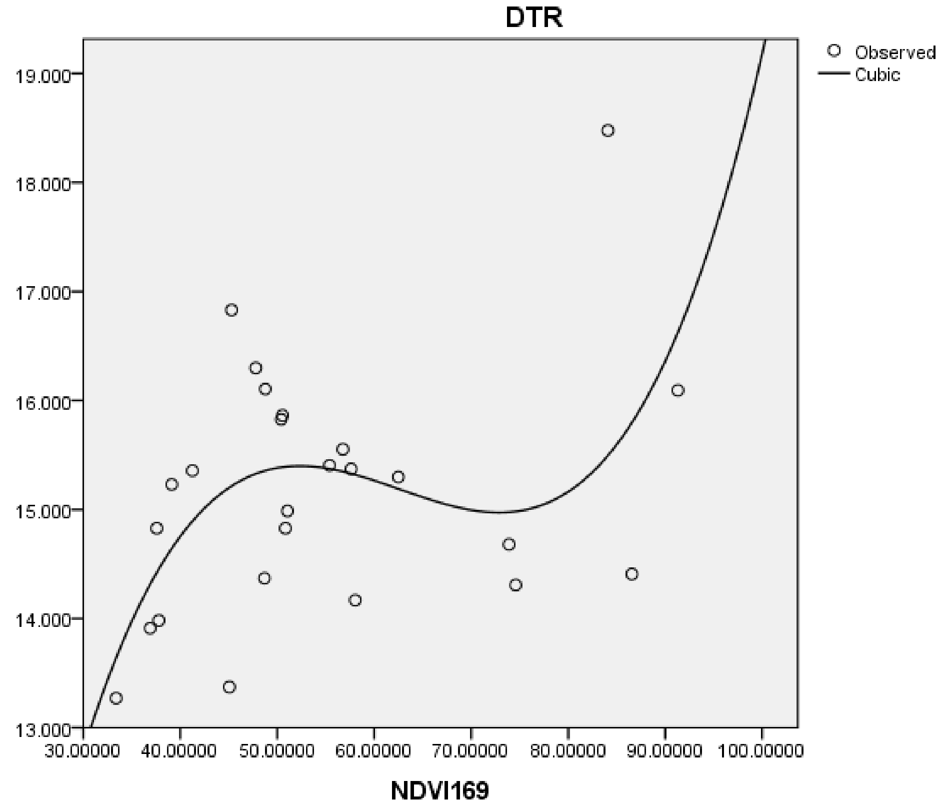
Equation	Model Summary					Parameter Estimates		
	R Square	F	df1	df2	Sig.	Constant	b1	b2
Cubic	.244	2.256	3	21	.112	-7.050	1.128	-.019

Model Summary and Parameter Estimates

Dependent Variable: DTR

Equation	Parameter Estimates
	b3
Cubic	9.860E-5

The independent variable is NDVI169.


DTR
19.000
18.000
17.000
16.000
15.000
14.000
13.000
30.00000
40.00000
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90.00000
100.00000
NDVI169
Observed
Cubic

APPENDIX B:

SUMMER 2013 DTR AVERAGE REGRESSIONS WITH NDVI

1 NDVI Pixel

Model Summary and Parameter Estimates

Dependent Variable: DTR

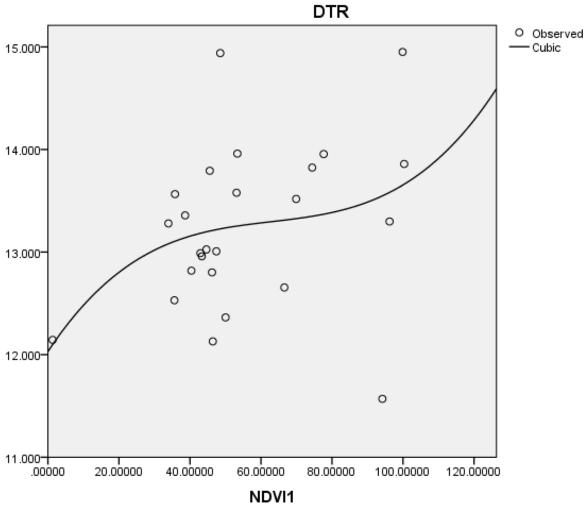
	Model Summary					Parameter Estimates		
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2
Cubic	.127	1.022	3	21	.403	12.030	.052	-.001

Model Summary and Parameter Estimates

Dependent Variable: DTR

	Parameter Estimates
Equation	b3
Cubic	4.072E-6

The independent variable is NDVI1.



9 NDVI Pixels

Model Summary and Parameter Estimates

Dependent Variable: DTR

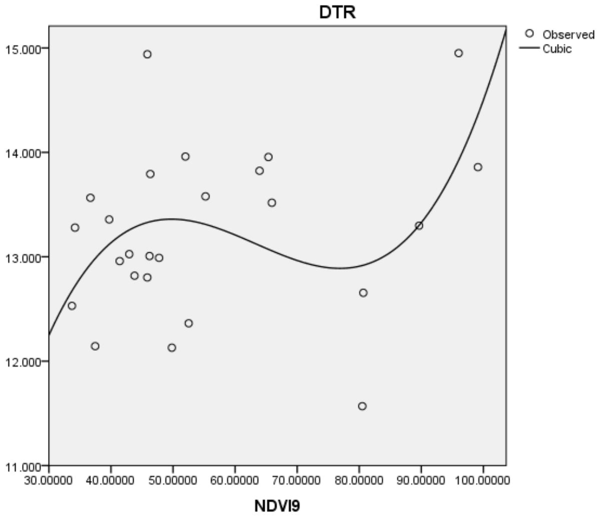
	Model Summary					Parameter Estimates		
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2
Cubic	.184	1.579	3	21	.224	2.800	.541	-.009

Model Summary and Parameter Estimates

Dependent Variable: DTR

	Parameter Estimates
Equation	b3
Cubic	4.720E-5

The independent variable is NDVI9.



25 NDVI Pixels

Model Summary and Parameter Estimates

Dependent Variable: DTR

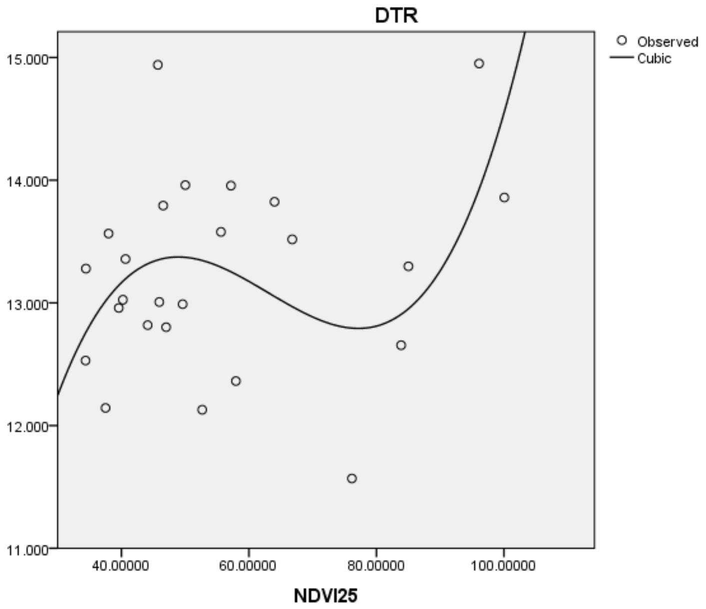
Equation	Model Summary					Parameter Estimates		
	R Square	F	df1	df2	Sig.	Constant	b1	b2
Cubic	.217	1.939	3	21	.154	2.123	.583	-.010

Model Summary and Parameter Estimates

Dependent Variable: DTR

Equation	Parameter Estimates
	b3
Cubic	5.156E-5

The independent variable is NDVI25.



49 NDVI Pixels

Model Summary and Parameter Estimates

Dependent Variable: DTR

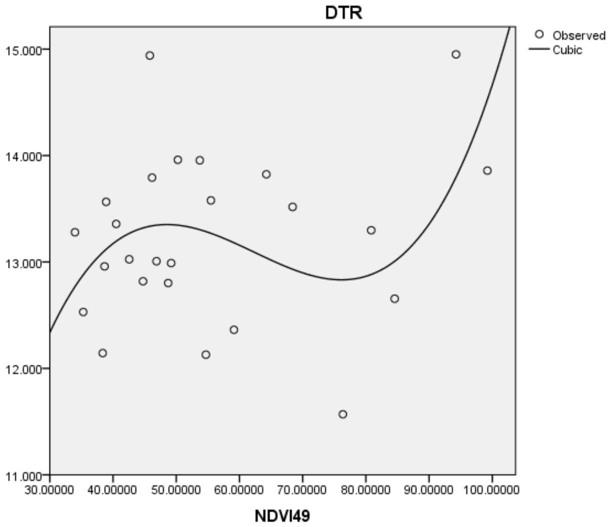
Equation	Model Summary					Parameter Estimates		
	R Square	F	df1	df2	Sig.	Constant	b1	b2
Cubic	.188	1.625	3	21	.214	2.912	.546	-.009

Model Summary and Parameter Estimates

Dependent Variable: DTR

Equation	Parameter Estimates
	b3
Cubic	4.931E-5

The independent variable is NDVI49.



81 NDVI Pixels

Model Summary and Parameter Estimates

Dependent Variable: DTR

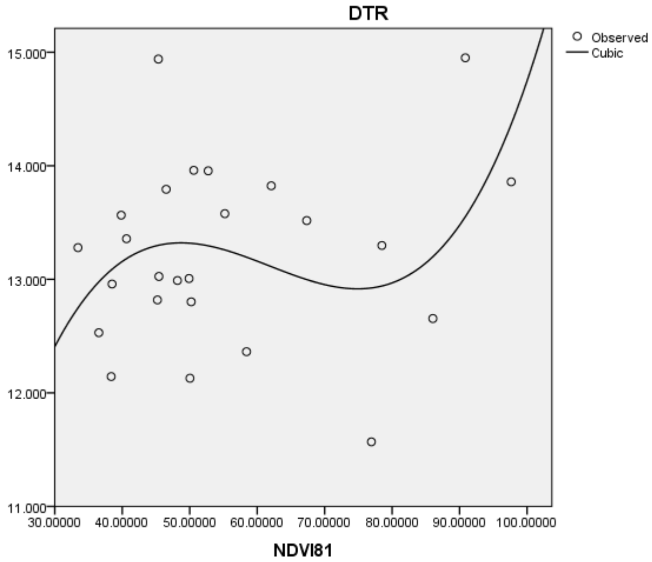
Equation	Model Summary					Parameter Estimates		
	R Square	F	df1	df2	Sig.	Constant	b1	b2
Cubic	.131	1.057	3	21	.388	3.914	.493	-.008

Model Summary and Parameter Estimates

Dependent Variable: DTR

Equation	Parameter Estimates
	b3
Cubic	4.509E-5

The independent variable is NDVI81.



121 NDVI Pixels

Model Summary and Parameter Estimates

Dependent Variable: DTR

Equation	Model Summary					Parameter Estimates		
	R Square	F	df1	df2	Sig.	Constant	b1	b2
Cubic	.116	.915	3	21	.451	2.194	.601	-.010

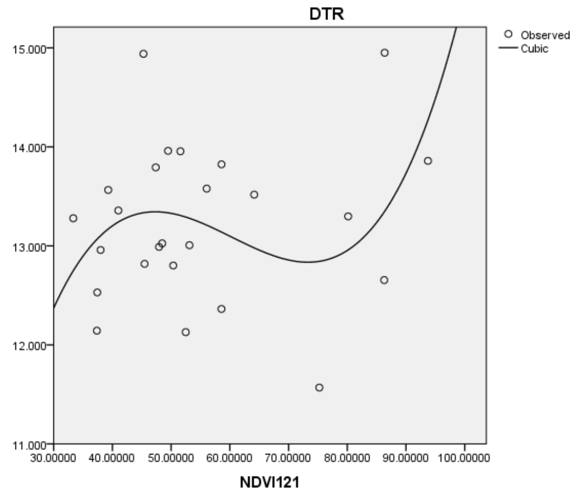
Model Summary and Parameter Estimates

Dependent Variable: DTR

Equation	Parameter Estimates
	b3

Cubic	5.780E-5

The independent variable is NDVI121.



169 NDVI Pixels

Model Summary and Parameter Estimates

Dependent Variable: DTR

	Model Summary					Parameter Estimates		
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2
Cubic	.090	.688	3	21	.569	2.170	.602	-.010

Model Summary and Parameter Estimates

Dependent Variable: DTR

	Parameter Estimates
Equation	b3
Cubic	5.819E-5

The independent variable is NDVI169.