EXAMINING *CULEX TARSALIS* (DIPTERA: CULICIDAE) POPULATION CHANGES WITH SATELLITE VEGETATION INDEX DATA

by

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Abstract

A zoonotic disease is any disease or infection that is naturally transmissible from vertebrate animals to humans. Over 200 zoonoses have been described (Zoonoses and the Human-Animal-Ecosystems Interface, 2013). Many zoonotic viruses are arboviruses, viruses transmitted by an infected, blood-sucking, arthropod vector (Hunt, 2010). There are several endemic arboviruses in the United States; some foreign arboviruses, such as Rift Valley fever (RVF) virus, are potential bioterrorism agents (Dar, 2013). Arboviruses, both endemic and foreign, threaten public health (Gubler, 2002) and therefore disease surveillance, vector control and public education are all vital steps in minimizing arboviral disease impact in the United States.

Mosquito-borne disease threats, such as West Nile virus and Rift Valley fever, are constant concerns in the United States and globally. Current strategies to prevent and control mosquito-borne diseases utilize vector distribution, seasonal and daylight timing, and variation in population numbers. Climate factors, such as availability of still water for development of immature mosquitoes, shade, and rainfall, are known to influence population dynamics of mosquitoes. Using 1995-2011 mosquito population surveillance data from Fort Riley, Kansas, we compared population numbers of *Culex tarsalis* (Diptera: Culicidae), a vector of several arboviruses including West Nile virus and potentially Rift Valley fever, to a satellite-derived index of climate, the Normalized Difference Vegetation Index (NDVI) anomaly. No correlation between the population numbers and NDVI anomaly was observed, which contrasts with results from similar analyses in other locations. These findings suggest a need for continued investigation into mosquito population dynamics in additional ecological regions of the United States to better describe the heterogeneity of environment-population relationships within and among mosquito species.

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Preface

A zoonotic disease is any disease or infection that is naturally transmissible from vertebrate animals to humans. Over 200 zoonoses have been described and may be caused by all types of pathogenic agents, including bacteria, parasites, fungi, and viruses (Zoonoses and the Human-Animal-Ecosystems Interface, 2013). Many zoonotic viruses are arboviruses, viruses transmitted by an infected, blood-sucking, arthropod (mosquito and tick) vectors (Hunt, 2010). There are several endemic arboviruses in the United States, with West Nile virus (WNV) being the leading cause of domestically acquired arboviral disease in people. However, several other arboviruses also cause seasonal outbreaks and sporadic cases and the majority of arboviruses are asymptomatic (Center for Disease Control and Prevention, 2013c). Some foreign arboviruses, such as Rift Valley fever (RVF) virus, are potential bioterrorism agents (Dar, 2013). Arboviruses, both endemic and foreign, threaten public health (Gubler, 2002) and therefore disease surveillance, vector control and public education are all vital steps in minimizing arboviral disease impact in the United States.

In this research, the *Culex tarsalis* mosquito population was studied. *Cx. tarsalis* is found throughout the entire United States. The rate of its lifecycle depends upon food availability and temperature and ranges from seven (7) days to four (4) weeks (Pahk, 2003). During the warm months, females oviposit egg rafts in newly flooded, freshwater substrates. *Culex spp*. lifespan is approximately two weeks. The females that emerge in late summer search for sheltered areas to hibernate for the winter and carry inseminated, undeveloped eggs, which require a blood meal to mature in the spring. However some females are able to mature their initial egg batch without a blood meal, known as autogeny, and oviposit 4-5 days after emergence (American Mosquito Control Association, 2013; Pahk, 2003). During the daytime, adults can be found resting in shaded areas and become most active in the few hours after sunset. *Cx. tarsalis* parasitize both avian and mammalian hosts. When populations are low in the spring, most females tend to feed on avian hosts. In the late summer these mosquitoes will seek mammalian hosts. This seasonal shift may be a significant factor in zoonotic viral transmission (Reisen, 1993; Pahk, 2003). *Culex tarsalis* has been known to transmit West Nile virus, Western Equine Encephalomyelitis virus, St. Louis Encephalitis virus and, in vitro, Rift Valley Fever virus (Turell et al., 2010; Reisen et al., 1993; Reisen et al., 2006; Gargan et al., 1988).

Rift Valley fever (RVF) is a viral disease most commonly observed in domesticated animals (such as cattle, buffalo, sheep, goats, and camels), but can cause disease in humans. RVF is generally found in regions of eastern and southern Africa and most of sub-Saharan Africa (Center for Disease Control and Prevention, 2013a). In September 2000, a RVF outbreak was reported in Saudi Arabia and subsequently, Yemen. This outbreak represents the first cases of RVF identified outside Africa (Center for Disease Control and Prevention, 2000) and supports that the range of RVF virus is expanding, making it an emerging disease. Currently there have been no reports of RVF virus in the United States (Center for Disease Control and Prevention, 2013a).

Outbreaks of RVF can cause significant economic losses and trade reductions. The virus causes disease and abortion in domesticated animals, an important income source. Additionally, livestock outbreaks of RVF increase contact between diseased animals and humans, which may lead to epidemics of RVF in humans (Center for Disease Control and Prevention, 2013a).

Humans can be infected with RVF virus from bites of infected mosquitoes but are more commonly infected after exposure to blood, body fluids, or tissues of RVF-infected animals. Several mosquito species act as vectors; as a result, the dominant mosquito species, which varies by region, will impact the common transmission cycles of RVF virus (Center for Disease Control and Prevention, 2013a). Factors that affect mosquito populations in general, such as temperature and rainfall, may also affect transmission. Infection through aerosol transmission of RVF virus has occurred in the laboratory environment. No human-to-human transmission has been documented. Transmission to a human infant in utero was first reported in 2006 (Rift Valley Fever, 2006; Arishi, 2006).

RVF virus has an incubation period of 2-6 days. In most human cases, an infected individual has no symptoms or a mild illness associated with fever and liver abnormalities. Ill patients may experience fever, weakness, back pain, and dizziness. Typically, patients recover within one week after onset of illness. 8-10% of people infected with RVFV develop much more severe symptoms. The most common complication is retinitis and ocular disease. Ocular disease, blurred and decreased vision, may occur 1-3 weeks after onset of initial symptoms. These lesions may disappear after 10-12 weeks but approximately 1 - 10% of affected patients may have permanent vision loss. Another complication is encephalitis which manifests as headaches, coma, or seizures. This occurs in less than 1% of patients and presents 1-4 weeks after first symptoms appear. Neurological deficits, sometimes severe, may persist post-infection and rarely encephalitis-associated death may occur. Hemorrhagic fever is a rare complication, occurring in less than 1% of overall RVF patients. Fatality for this complication is around 50%. Symptoms of hemorrhaging include jaundice, vomiting blood, bloody stool, or bleeding from gums, skin, nose, and injection sites. Death usually occurs 3-6 days after the onset of hemorrhagic symptoms. Overall, approximately 1% of humans infected with RVF virus die of the disease. Infected livestock mortality rates are significantly higher (10-20% in adults, 70-100% in young), with RVFV infection causing abortion in nearly 100% of pregnancies (Center for Disease Control and Prevention, 2013a).

Because most human cases of RVF are mild and self-limiting, a specific treatment for RVF has not been established. The rare, but serious, cases are generally limited to supportive care. Prevention in humans is focused on minimizing mosquito population and contact and taking proper precautions around infected tissue and blood. No vaccines are currently available for human use. Different types of vaccines for veterinary use are available but are not currently used in the United States. The killed vaccines are not practical in routine animal field vaccination because of the need of multiple injections. Live vaccines require a single injection but are known to cause birth defects and abortions in sheep and induce only low-level protection in cattle. (Center for Disease Control and Prevention, 2013a).

Introduction of Rift Valley Fever virus to the United States may have devastating consequences so understanding potential transmission vectors and reservoir species is vital to minimize risk of introduction and effects if the virus is introduced.

Mosquitoes, especially *Culex spp*., are the main transmitter of West Nile Virus in nature (CDC, 2013b). West Nile Virus (WNV) was first reported in the United States in 1999 with outbreaks occurring every summer since. It has been detected in all 48 continental states. According to the CDC (2013b), 70-80% of human infections are asymptomatic. Most symptomatic cases will develop a fever with or without headache, body aches, joint pains, vomiting, diarrhea, or rash. Fatigue and weakness in these patients may last for weeks to months after the rest of the disease has resolved. Less than 1% of people who are infected will develop a serious neurologic illness such as encephalitis or meningitis. Symptoms in these cases include headache, high fever, neck stiffness, disorientation, coma, or paralysis. Mortality rate of those severely affected is 10% and survivors may have permanent neurological deficits. Treatment is symptomatic (CDC, 2013b).

Arboviral Encephalitis is a disease caused by several arboviruses, including St. Louis Encephalitis (SLE), Western Equine Encephalitis (WEE), Venezuelan Equine Encephalitis (VEE), Eastern Equine Encephalitis (EEE), La Crosse virus and other California serogroup viruses (Center for Disease Control and Prevention, 2009). *Cx. tarsalis* is known to transmit SLE and WEE (Reisen et al., 1993). SLE is rare but periodic outbreaks and epidemics have primarily occurred in the Mississippi Valley and along the Gulf Coast. Most people who are infected with SLE virus are asymptomatic or have mild, flu-like illness. However, in some individuals, especially the elderly, SLE virus can cause serious illness including fever, headache, stiff neck, disorientation, and altered level of consciousness. SLE may progress to coma, convulsions, and paralysis. Treatment is symptomatic and SLE virus cannot be transmitted person to person (Center for Disease Control and Prevention, 2010). WEE is closely related to Eastern and Venezuelan Equine Encephalitis viruses. Similar to SLE virus, symptoms range from mild, flu-like illness to coma and death. Neurologic deficits, mild to severe, may remain post-treatment. WEE is rare in humans in the United States (Center for Disease Control and Prevention, 2005).

The Normalized Difference Vegetation Index (NDVI) uses satellite multispectral imagery to measure and monitor plant growth, vegetative cover, and biomass production. The NDVI is linked to temperature, rainfall, and plant productivity (Department of the Interior, 2010). The NDVI is unitless, but numerically ranges from -1 to 1, with 0.5 or above indicating dense vegetation and values ≤ 0 as no vegetation (University of Reading, 2002). The NDVI anomaly value, the numerical difference of the measure compared to the long term average (i.e. 20-25 years) for a certain time period such as the month of July or the 30th week of the year, is often measured to examine the deviation of NDVI from the long term mean (Department of the Interior, 2010).

According to the World Health Organization (2013), "*Reducing public health risks from zoonoses and other health threats at the human-animal-ecosystems interface (such as antimicrobial resistance) is not straightforward. Management and reduction of these risks must consider the complexity of interactions among humans, animals, and the various environments* *they live in, requiring communication and collaboration among the sectors responsible for human health, animal health, and the environment."* The objective of this study was to examine *Cx. tarsalis* population change in Fort Riley, Kansas, in relation to the time of year and patterns of change in NDVI, which may be useful in predicting future changes in *Cx. tarsalis* populations. The results of this study may be useful in developing and evaluating vector population control methods that can limit transmission of potential emerging diseases, such as RVF, to humans and susceptible wildlife or livestock in the United States.

Chapter 1 - Introduction

Increasing concern regarding mosquito-borne diseases requires a better understanding of mosquito vector population biology. Environmental factors that may influence the numbers of potential vectors are important. Understanding these factors will allow better allocation of resources to efficiently prevent or reduce outbreaks. Several mosquito-borne viral diseases, such as Rift Valley fever (RVF) and dengue fever, show increased movement outside of endemic areas as a result of natural processes of dispersal as well as accidental introduction (Gubler, 2002). They could potentially be used as agents of bioterrorism and thus signify emerging threats to the United States. Understanding the role of mosquito vectors in range expansion of emerging mosquito-borne disease threats will be a critical element of systems designed to prevent or detect and contain the arrival of these diseases.

Culex tarsalis (Diptera: Culicidae) is a mosquito endemic in North America and capable of transmitting West Nile virus (WNV) in nature, Rift Valley fever virus (RVFV) in the laboratory, several equine encephalitis viruses, and many other arboviruses (Reisen, 1993; Center for Disease Control and Prevention, 2013b; WHO, 2010). *Culex* species are known to lay eggs in newly flooded freshwater and resting, fed adults are found in shaded areas during the day (Pahk, 2003). One California study showed that warm winter temperatures are associated with increased abundance of *Culex* females (Reisen et al., 2010). *Culex spp.* females feed on both birds and mammals; typically, most females feed on birds in the spring and transition to mammalian hosts as the mosquito population increases (Pahk, 2003).

Culex tarsalis in North America has a strong capability to transmit RVFV in the laboratory (Gargan et al., 1988), and the species was the most efficient at transmitting RVFV of eleven mosquito species assayed in one laboratory study (Turell et al., 2010). Several studies of *Culex spp.* in the United States have been carried out in the past ten years in part due to the arrival of WNV in 1999. One study showed *Culex. spp* capable of vertical transmission and overwintering of WNV (Nelms et al, 2013). A Canadian study described an expanding territory for *Cx. tarsalis* (Chen et al., 2013b). In other research nearly 100 different host species were identified from 1,487 bloodmeals from *Culex spp*. (Theimann et al, 2012). Although *Cx. tarsalis* rarely fed on humans in this study, it is important to recognize that the diversity of potential hosts that were identified coupled with large mosquito population sizes in nature and an expanding territory could indicate the potential for high transmission rates with epidemiological cycles involving *Culex spp.* that will increase risk of exposure of humans to WNV.

Another study found that the transmission of WNV increased with higher mean temperature and elevated time lagged mean temperature (Chen et al., 2013a). A lower infection rate was found with increasing precipitation even though mosquito population numbers were higher. Increased temperature fluctuation and wetland land cover were also associated with decreased infection rate (Chen et al., 2013a).

The normalized difference vegetation index (NDVI) uses satellite multispectral imagery to measure and monitor plant growth, vegetative cover, and biomass production. The NDVI is linked to temperature, rainfall, and plant productivity (Department of the Interior, 2010). This information could potentially be used to develop advanced warning systems for droughts and famines, for example by evaluating time series changes in plant density (Britch et al., 2008; Chuang et al., 2012). The NDVI is unitless, but numerically ranges from -1 to 1, with 0.5 or above indicating dense vegetation and values ≤0 as no vegetation (University of Reading, 2002). The NDVI anomaly value, the numerical difference of the time specific measurement compared to a long term average (i.e. 20-25 years) for a certain time period such as the month of July or the 30th week of the year, is often measured to examine the current deviation from the long term mean of NDVI (Department of the Interior, 2010). Because mosquito populations have been correlated to rainfall and/or temperature, many studies have examined the relationship between specific mosquito populations and NDVI (Britch et al., 2008; Liu et al., 2006; Shililu et al., 2003; Gleiser et al., 1997; Apiwathnasorn et al., 2006).

Studies examining populations of *Culex spp.* in relation to NDVI are few. One study concluded that *Culex spp.* in Georgia, California and Washington military installations may not always track NDVI data because habitat for some *Culex spp.* includes artificial bodies of water flooded by human activity, such as storm drains and containment ponds. (Britch et al., 2008). Other studies have demonstrated a good correlation between both *Aedes* and *Culex spp.* populations in RVF endemic regions in Africa (Linthicum et al, 1987, 1990). Several other studies show a strong correlation between NDVI and populations of other mosquito species, such as *Anopheles spp*. (Diptera: Culicidae), which are important malaria vectors (Dambach et al., 2012; Liu and Chen, 2006; Rueda et al., 2010). This suggests that more research is needed to determine if *Culex spp.* population dynamics in additional regions may be related to NDVI.

The objective of the present study was to examine *Cx. tarsalis* population change in Fort Riley, Kansas, in relation to the time of year and patterns of change in NDVI. In particular, mosquito population changes that track seasonal timing and/or dynamics of NDVI may be useful in predicting future changes in *Cx. tarsalis* populations in order to develop and evaluate vector population control methods to limit transmission of potential emerging diseases such as RVFV to humans and susceptible wildlife or livestock in the United States.

Chapter 2 - Materials and Methods

Mosquito population surveillance data were collected by U.S. Army preventive medicine teams at Fort Riley during routine longitudinal surveillance for nuisance and disease vector species. The collections were conducted with New Jersey light traps (NJLT) at sites across the installation from 1995 to 2011. Population data included identification of species and sex. Number and position of NJLT varied by year but some trap locations were constant over all of the years.

In order to account for variation in the number of NJLT and variation in the frequency of surveillance activity across the 1995-2011 Fort Riley data set, we derived a count of female mosquitoes per trap-night index for each week and month of the study. The trap-night index was determined by multiplying the number of traps deployed by the total number of nights surveillance was carried out in a week or month. For example, two traps placed for two nights, or one trap placed for four nights, would equal four trap-nights. Data was collected by month for 1995-2000 and by week for 2001-2011. Therefore the weekly data was summed to have monthly data for 2005-2011. This process generated a count of weekly and monthly average mosquitoes per trap night. Mosquito trap data are typically not normally distributed and tend to be skewed towards zero (Lester and Pike, 2003; Masuoka et al., 2009; Chuang et al. 2011; Cleckner et al., 2011) so we performed a log-transformation on the raw trap data before analysis with the form ln (x+1), where x was the number of female *Cx. tarsalis* collected by one trap in one night.

The North American NDVI satellite data sets were obtained monthly from 1995 to 2000 and weekly from 2001 to 2011 from the NASA Goddard Space Flight Center, and data were compiled as described in Britch et al., (2008). The raw NDVI data were reported as a matrix of 8 km squares of the earth's surface and NDVI data from the 16 adjacent squares that covered the Fort Riley area (Appendix A). The mean NDVI values were the averages of the raw monthly or weekly NDVI. The NDVI anomaly values represent the current deviation of the raw NDVI from the long term mean for the month or week. The relationship between *Cx. tarsalis* counts per trap night and NDVI anomaly was analyzed using linear regression including month or week and year as factor variables using STATA 12.1 [StataCorp LP, College Station, TX].

Additionally, the monthly NDVI anomaly value was analyzed at the simultaneous dates and lagging one month behind the mosquitoes/trap night variable. The weekly NDVI anomaly value was analyzed at the simultaneous dates and a two-week and a four-week lag behind the mosquitoes/trap night variable.

Only May through October was analyzed because of the limited amount of mosquito data available for January through April and November through December.

Chapter 3 - Results

Figure 3.1 shows the monthly female *Cx. tarsalis* per trap-night and the monthly raw NDVI and the monthly NDVI anomaly values.

Figure 3.2 shows the weekly female *Cx. tarsalis* per trap-night and the average weekly raw NDVI and the weekly NDVI anomaly values.

Results from the monthly and weekly data regression analysis are shown in Table 3.1 and Table 3.2 respectively.

Figure 3.1 Monthly Comparison of Mosquitoes/Trap-Night to NDVI

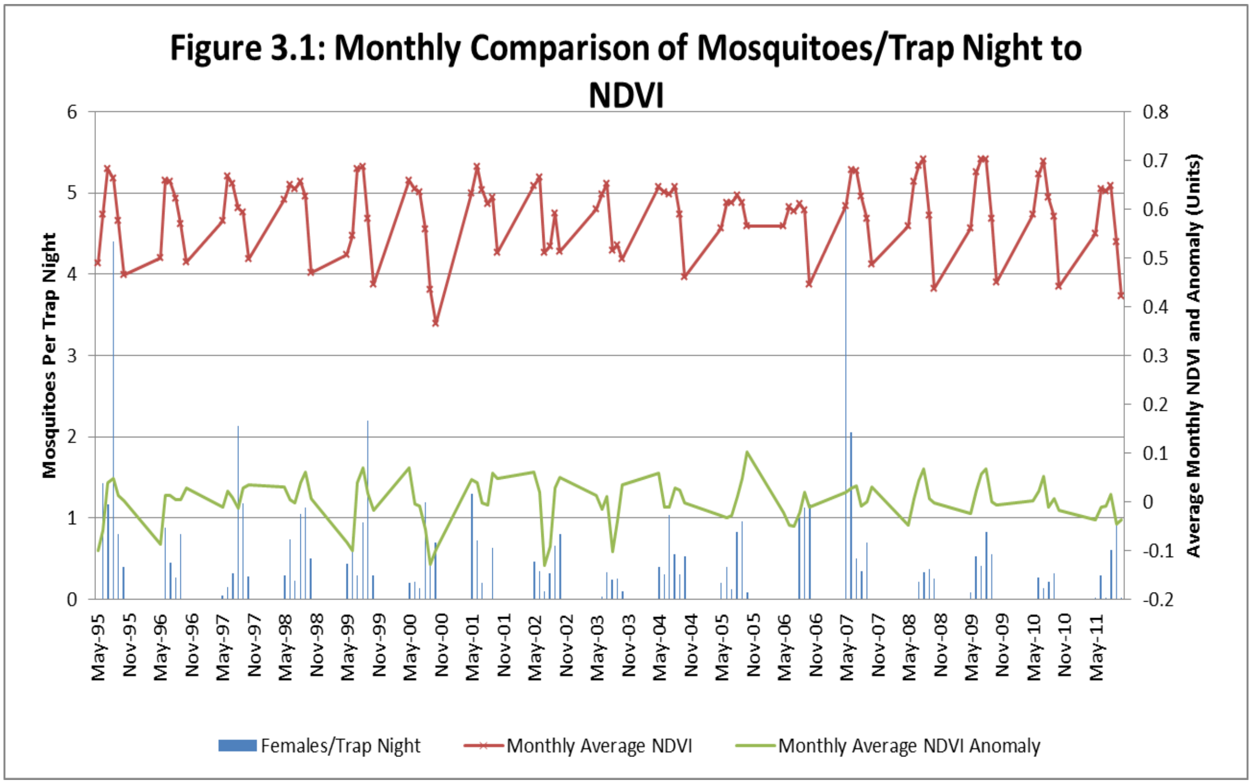

Figure 3.1: This figure compares the monthly female *Cx. tarsalis* per trap night to the average monthly raw NDVI and the NDVI anomaly values from May to October, 1995 to 2011.

Figure 3.2 Weekly Comparison of Mosquitoes/Trap Night to NDVI

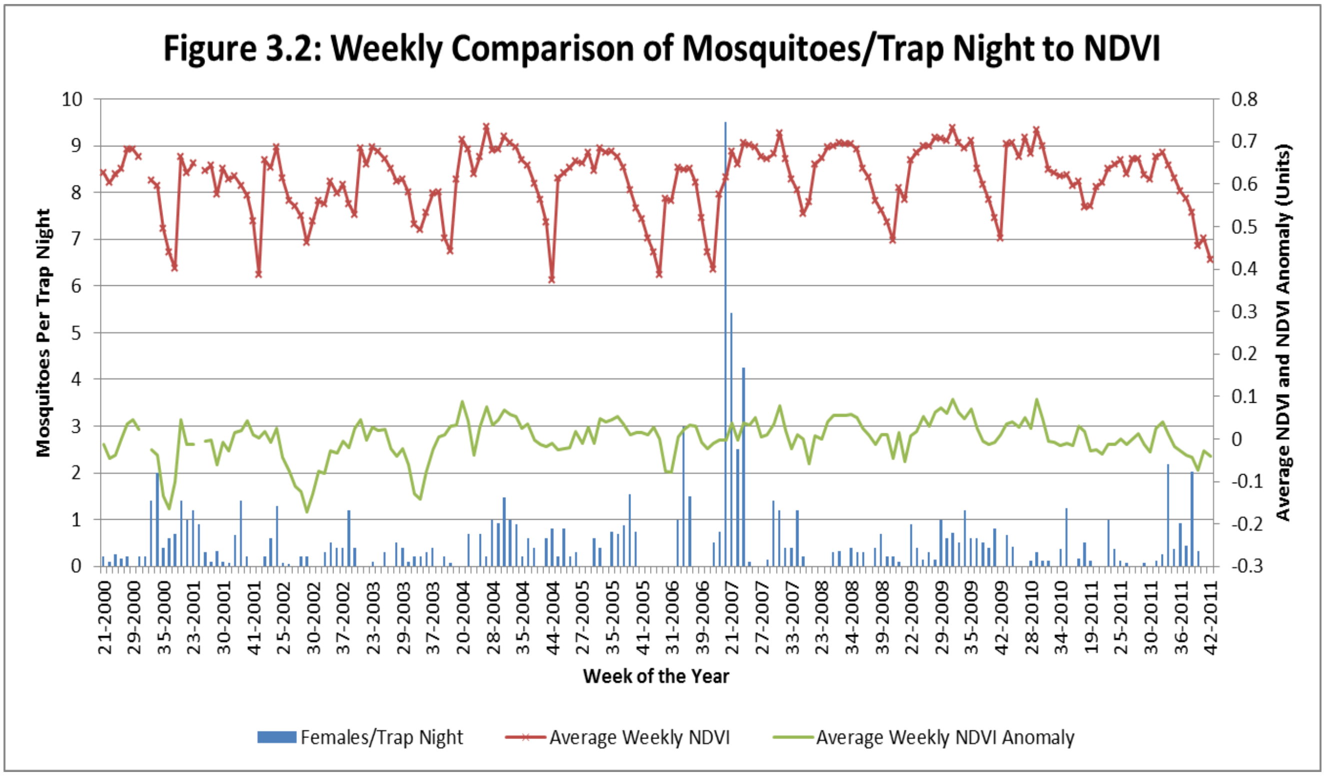

Figure 3.2: This figure compares the weekly female *Cx. tarsalis* per trap night to the average weekly raw NDVI and the NDVI anomaly values from May to October, 2001 to 2011.

Table 3.1 The Statistical Analysis Results for the Monthly Data Set

Table 1: This table shows the results of linear regression between the natural log of the monthly average female *Cx. tarsalis*/trap-night compared to the monthly average NDVI anomaly.

Table 3.1: The statistical analysis results for the monthly average females/trap-night compared to the monthly average NDVI anomaly					
Variable	Coefficient	Standard Error	P>|T|	95% Confidence Interval	
NDVI Anomaly	0.205661	0.1260355	0.107	-0.04547	0.4567924
NDVI Anomaly with a Lag of One Month	-0.115814	0.1245876	0.356	-0.3641165	0.1324889

Table 3.2 The Statistical Analysis Results for the Weekly Data Set

Table 2: This table shows the results of linear regression between the natural log of the weekly average female *Cx. tarsalis*/trap-night compared to the weekly average NDVI anomaly.

Table 2: The statistical analysis results for the weekly average females/trap-night compared to the monthly average NDVI anomaly

Variable	Coefficient	Standard Error	P>|T|	95% Confidence Interval	
NDVI Anomaly	0.511418	0.267352	0.058	-0.0169022	1.039738
NDVI Anomaly with a Lag of Two Weeks	-0.51913	0.2676213	0.054	-1.048042	0.0097827
NDVI Anomaly with a Lag of Four Weeks	-0.143165	0.2755147	0.604	-0.6877401	0.401411

The linear regression analysis resulted in no relationship (p=0.107) between the natural log of the average monthly mosquitoes/trap-night to the average NDVI anomaly with no time lag. Year and month of the year were each significantly associated with log of the average monthly mosquitoes/trap-night (p<0.05). Only 1996 (lower), 2006 (higher) and 2011 (lower) were significantly different from the 1995 baseline. None of the months of the year were significantly different than the May baseline. Similarly, the linear regression statistical analysis resulted in no relationship (p=0.356) between the natural log of the average monthly mosquitoes/trap-night to the average NDVI anomaly with a month lag. Year and month of the year were each significantly associated with log of the average monthly mosquitoes/trap-night with a month lag in NDVI (p<0.05). Only 1996 (lower), 2006 (higher) 2008 (lower) and 2011 (lower) were significantly different from the 1995 baseline. May was significantly higher than July (p=.028).

The linear regression analysis of the natural log of the average weekly mosquitoes/trap-night to the average NDVI anomaly with no time lag trended toward significance (p=0.058) with a positive coefficient. Year and month of the year were each significantly associated with log of the average weekly mosquitoes/trap-night (p<0.05). All years were statistically similar to 1995 data with the exception of 2007 (p=0.016), which was higher. None of the weeks of the year were significantly different than the week 18 (the first week of May) baseline. The linear regression analysis of the natural log of the average weekly mosquitoes/trap-night to the average NDVI anomaly with a two week time lag also trended toward significance (p=0.054) but with a negative coefficient. Year and month of the year were each significantly associated with log of the average weekly mosquitoes/trap-night (p<0.05). All years were statistically similar to 1995 data with the exception of 2007 (p=0.003), which was higher. None of the weeks of the year were significantly different than the week 18 (the first week of May) baseline.

The linear regression analysis of the natural log of the average weekly mosquitoes/trap-night to the average NDVI anomaly with a four week time lag was not significant (p=0.604). Year was significantly associated with log of the average weekly mosquitoes/trap-night (p<0.05), however week of the year was not significantly associated for this model (p=0.052). All years were statistically similar to 1995 data with the exception of 2007 (p=0.031), which was higher. None of the weeks of the year were significantly different than the week 18 (the first week of May) baseline.

Chapter 4 - Discussion

In summary, the linear regression identified no relationship ($p > 0.05$) between the average female *Cx. tarsalis* population per trap night and average NDVI anomaly for the monthly averages but trended toward significance for the weekly averages (the p-value approached 0.05 but was still >0.05.) Results approached significance for the natural log of the weekly female/trap-night as it tended to increase with NDVI anomaly ($p = 0.058$) and tended to decrease with the 2-week lag of NDVI anomaly ($p = 0.054$). The year 2007 was always statistically higher ($p < 0.05$) than 2000 (in the weekly analysis.) This is reflected on Figure 3.1 and Figure 3.2. The NDVI Anomaly values with both a two week and a four week lag had negative coefficients. The reason for this is not clear. It is possible that there is a lag between rainfall and NDVI change that is longer than the lag between rainfall and *Culex spp.* population changes such that the *Culex spp*. population is decreasing at the time NDVI changes. Perhaps the high NDVI is just predictive of regressing subsequent movement of the NDVI toward the long term mean. This suggests the relationship between weather, NDVI and mosquito populations is complex and further investigation is needed.

The overall lack of a relationship is in contrast to research performed with mosquito population data from several U.S. military installations that found "the NDVI signal may actually be visible late in the previous month or early in the current month and so be useful operationally as a warning regarding potential mosquito-borne disease activity" (Britch et al., 2008). Our models that included time lags between the NDVI and mosquito trap night data were intended to identify any value of NDVI as a leading indicator of mosquito numbers. However, although Britch et al. (2008) did not include data for *Cx. tarsalis,* the study did hypothesize that *Culex* species may not always track NDVI data because their habitat includes bodies of water associated with human activity, such as storm drains and containment ponds, and this could explain of the lack of statistical significance in the data from the current study. This may explain our failure to find a clear effect of NDVI on mosquito numbers. The reason for the sign change associated with the NDVI for weekly models with no lag and a two-week lag is not clear, as discussed above.

Mosquito-borne diseases, such as Rift Valley fever and dengue fever, threaten human and animal health alike. An understanding of vector population change and vector epidemiology is crucial in minimizing these diseases and managing disease transmission. Our resources are more efficiently used when paired with this knowledge.

Future studies comparing NDVI to strike rate, the number of feedings per time period, could give us a better idea of transmission rates and health risk in relation to mosquito-borne diseases. Comparing NDVI to how many feedings per time period along with mosquito population numbers would also valuable to creating an epidemic predictive model. These mosquito characteristics are important in regards to disease transmission.

Population numbers based on terrain, such as availability of shade and still water sources, would also be beneficial, particularly for *Cx. tarsalis*. Information from these possible future studies may help determine in what areas analyzing NDVI as a sole predictor could be useful.

Geographical movement and population numbers of host species may affect the transmission of diseases that are primarily those of mammalian livestock and wildlife ailments, such as Rift Valley fever. If an outbreak were to occur, host populations would play an important role in the spread of disease, since *Culex* species are only known to travel up to 27 km in host-seeking flights (Pahk, 2003). Therefore both host and mosquito populations are important in predicting outbreaks of disease.

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Appendix A - NDVI Grid Cells

Map of the boundary of the Fort Riley military reservation (green stippling) with the sixteen 8km NDVI grid cells that were averaged to derive the mean NDVI value for the area for each month of each year of the 1995-2011 study period.