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Geographic Analysis of West Nile Virus in the Upper Minnesota River Valley: A GIS and Multi-temporal Remote Sensing Approach

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Geographic Analysis of West Nile Virus in the Upper Minnesota River Valley:

A GIS and Multi-temporal Remote Sensing Approach

By

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Dedication

This piece is dedicated to my family, parents and brother, for if it were not for their continued support the pursuit and completion of an advanced degree would not have been possible. I thank them dearly for my passionate ability to embrace life, freely take risks and remain humble despite all my personal achievements. A special thanks to Dr. Delany Sturgeon for never doubting that we could overcome anything and I would thrive in all my endeavors.

Acknowledgement

I would like to extend great thanks to the faculty at Minnesota State University in Mankato and specifically the Geography department. I would also like to thank all of my professors during my time here for making my education at MNSU outstanding and unparalleled in all aspects.
It is the professors that make a program what it is and those here are easily approachable, have great passion for their craft and bear an immense depth of knowledge that is always made available. The greatest of appreciate is extended directly to my committee members; Forrest Wilkerson, PhD, Ginger Schmid, PhD and Cindy Miller, PhD, without their vast knowledge this project would have been much more difficult.

"Learn from yesterday, live for today, hope for tomorrow. The important thing is to not stop questioning." - Albert Einstein

Table of Contents

Chapter 4: Geographic Analysis and Patterns of West Nile Virus: 2002-2012

Chapter 5: Discussion and Conclusions

List of Figures

List of Tables

Abstract

Throughout human evolution civilizations have been faced with implications from infectious diseases caused by various environmental factors. These connections were recognized as far back as the 5th century by Hippocrates and since several key advances have been realized and will be addressed in this an environmental and physical geography of disease. Arthropod or vector-borne viruses are among the most common pathogens introduced into the modern human population. West Nile Virus is considered endemic in most parts of the world and appeared in the United States in 1999 with 62 confirmed cases in an urban New York location. Since its first appearance in the United States the proliferation has been rapid and exponential with many contributing factors influencing its spread. This research will examine factors contributing to the increased prevalence of West Nile Virus (WNV) in the Upper Minnesota River Valley, Minnesota, USA between the years 2002 to 2012. A historical walk through the diverse world of medical geographic research will be analyzed as well. This will allow the basis for this research to be clearly defined and built upon. The advent and ever-increasing functionality of remote sensing and geographical information science (GIS) technologies enables a detailed analysis of factors to be undertaken with such an environmentally connected pathogen. This paper utilizes GIS and remote sensing techniques to analyze changes in climate, land cover, population and disease patterns that are impacting the prevalence and distribution of the disease.

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This thesis has been examined and approved by the following members of the student's committee.

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Forrest Wilkerson, PhD

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Ginger Schmid, PhD

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Cynthia Miller, PhD

Chapter One

An Exploration of Medical Geography and Vector-Borne Disease

I. Introduction

Medical geography is a specialty discipline in the diverse and complex interdisciplinary field of geography. Medical geography specializes in healthcare research that involves spatial patterns of disease, cultures of healthcare, healthcare disparities, and the economies of healthcare in the world. In this discipline of geography there lies two subdivisions, medical geography and health geography. The focus of this research will be in the landscape epidemiology arm of medical geographic research, which in addition to the spatial patterns of disease involves analysis of environmental factors such as climate, elevation, and land cover and how those attributes impact the prevalence of the disease.

Medical Geography vs. Health Geography

Medical geography is defined as "the study of the relation between geographic factors and disease" by Merriam-Webster online dictionary. This definition is certainly simplistic and unassuming for such a complex, dynamic and theory laden discipline of geographic research. Medical geography has also been known as health geography; however, following an extensive literature review it is clear that the two geographies exhibit different traits and are utilized in differing research areas. Medical geography is a geographic research discipline that is generally divided into two sub-categories, landscape epidemiology and/or spatial epidemiology, both of which are concerned with the human-environment interaction in relation to disease and is the underlying basis for this thesis. Landscape epidemiology, sometimes called spatial epidemiology, is a sub-discipline of medical geography that uses environmental conditions as explanatory variables in the study of disease or other health phenomena (Young et al., 2013). Spatial epidemiology encompasses many more aspects relating to infectious diseases and their abundance among human populations. Spatial epidemiology is the description and analysis of geographic variations in disease with respect to demographic, environmental, behavioral, socioeconomic, genetic, and infectious risk factors (NIH, 2004).

Health geography is an aspect of geographic research that is concerned with access to healthcare, economies of healthcare, healthcare policy and social behaviors in relation to personal health (Earickson, 2009). Health geography is a close relative of medical geography, sharing a focus on geographical variations in health and healthcare. Its specific concern is with a social model of health and particularly with a definition of health that emphasizes positive health and wellness over death and disease. It has also been particularly concerned with health-related behaviors such as diet, drinking, smoking, and exercise and with the provision of healthcare outside medical settings. Health geography emerged from medical geography over the past 30 years and the process of emergence is continuing (Moon, 2009).

Medical geography and its related sub-category of landscape epidemiology is the more appropriate approach to the study of West Nile Virus in the Upper Minnesota River Valley in that the disease and its prevalence is most likely directly tied to the topography and climate that reside in the region. These factors when combined with population and additional physical geographic data will allow a better understanding of WNV in southern Minnesota.

Humans and Emerging Infectious Disease

The interaction of humans and their environment has long been recognized since the 5th century and the time of Hippocrates (Pappas, Kiriaza, and Falagas, 2008). However, it wasn't until the early 20th century that scientists began to realize the immense impact our surrounding environment has on human health and mortality. From the plagues of biblical times to the HIV pandemics of recent times, infectious diseases have played an indisputably major role in human history. The continuous expansion of human populations since prehistoric times has led to successive invasions of infectious diseases by an increasing number of different pathogens.

Much of that infectious disease introduced into human populations is a result of environmental factors and by vectors such as mosquitos or fleas. Infectious diseases such as bubonic plague have the possibility of creating high mortality rates and decimating populations. Similar to the research focus of this thesis concerning West Nile Virus the cause of bubonic plague is that of a vector, a flea.

Plague is a bacterial infection found mainly in rodents and their fleas, but via those fleas it can sometimes leap to humans. When it does, the outcome can be horrific, making plague outbreaks the most notorious disease episodes in history (National Geographic, 2014).

The most famous and devastating vector outbreak in human history concerns the bubonic plague also known as the “Black Death”. The infamous medieval plague known as the Black Death in the 14^{th} century killed an estimated 25 million people in Asia and Europe, one third of Europe’s population (National Geographic, 2014). The plague still exists today on all continents because the vector transmission cycle still exists and is able to complete itself. As we can surmise from this historical event, today’s emerging infectious diseases such as WNV can with the right conditions create pandemics that significantly impact human populations. The right conditions are being provided as we detrimentally change the climate we live in by our own anthropogenic actions. There is no doubt that all vector borne diseases are very sensitive to climatic conditions (Enserink, 2008; Randolph and Rogers, 2010). Many such diseases have shown a marked increase in both distribution and incidence during the past few decades, just as human-induced climate change is thought to have exceeded random fluctuations (Randolph, 2010). Emerging and re-emerging mosquito borne diseases in temperate regions have become progressively more common in recent years as ever-increasing human and vector mobility creates conditions that are favorable for diffusion (Enserink, 2008, Randolph and Rogers, 2010).

The History and Impact of West Nile Virus

Mosquitos, No animal on earth has touched so directly and profoundly the lives of so many human beings (Spielman and D'Antonio, 2001). West Nile Virus (WNV) is a disease commonly transmitted by mosquitos and is endemic to nearly all parts of the inhabited world. WNV has become endemic in the United States, with ongoing potential for seasonal epidemic transmission at the local, regional, or national level (CDC surveillance, 2013). WNV is considered an arbovirus which is defined as, any of various RNA viruses (as the causative agents of equine encephalitis, sandfly fever, and West Nile fever) transmitted chiefly by arthropods, by Merriam-Webster dictionary. West Nile virus is currently the most widely distributed arbovirus in the world, occurring on all continents and causing sporadic cases and outbreaks of human and equine disease in Europe (Western Mediterranean and southern Russia between 1962 and 1964, Belarus and Ukraine in the 1970s and 1980s, Romania in 1996 and 1997, Czechland in 1997, and Italy in 1998) and the Americas (Savuta et al., 2008). Figure 1 is a map representative of significant known and documented epidemic outbreaks of WNV that have occurred in human populations.

West Nile Virus was first isolated from a woman in the West Nile District of Uganda in 1937 (Smithburn et al, 1940). The virus is taxonomically placed in genus *Flavivirus* and the family *Flaviviridae* and is considered a zoonotic arbovirus. A zoonotic disease is defined as an infectious disease that is transmitted between species from animals to humans (usually vectors); it is not transmitted from human to human or from human to animal.

However, in the case of WNV the typical transmission cycle is chiefly maintained between avian hosts and the mosquitos (vectors) with humans being incidental or dead end hosts. Figure 2 is a Centers for Disease Control and Prevention (CDC) representation of the WNV transmission cycle.

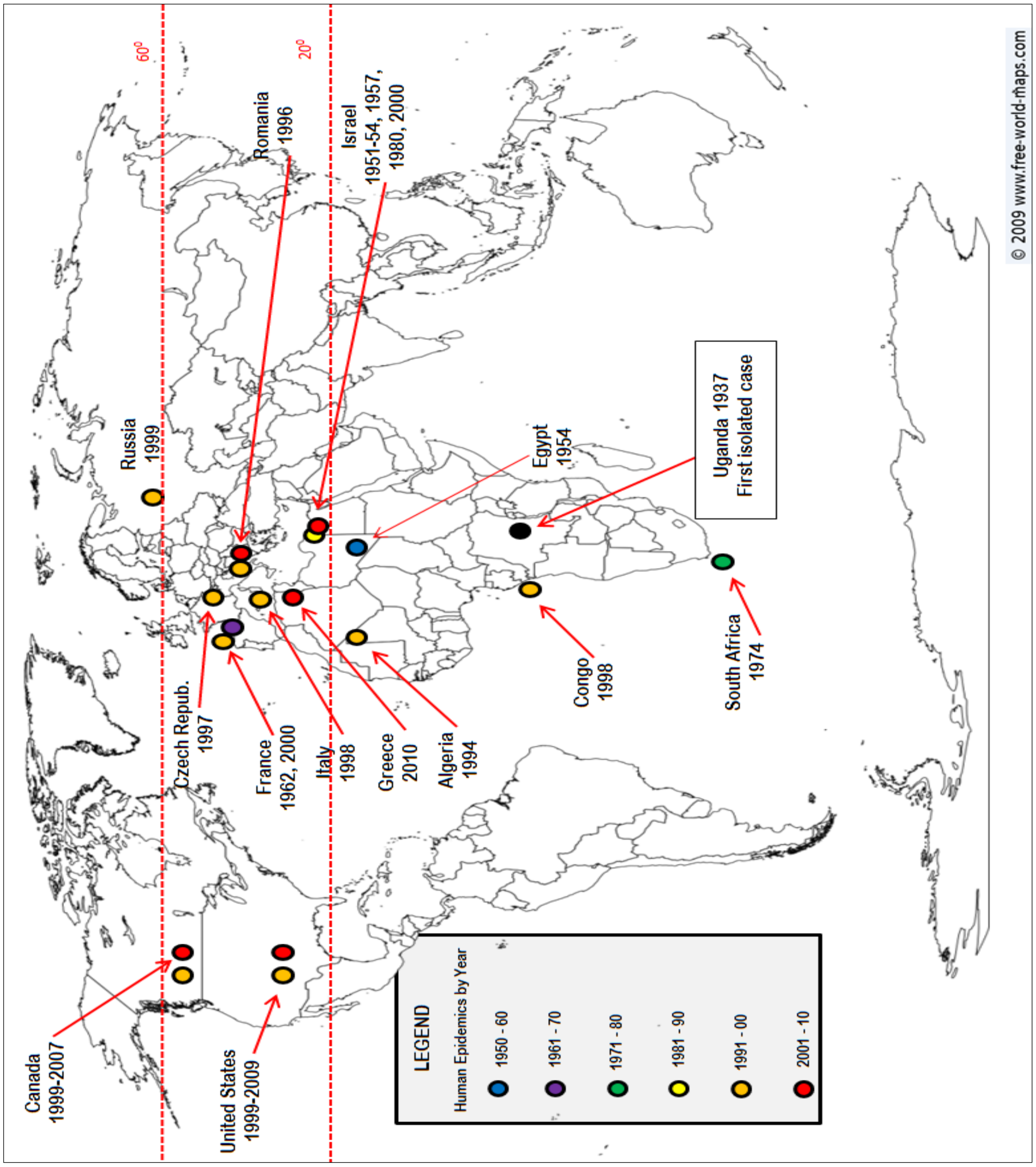


Figure 1: Idealized map of known epidemics in the modern human populations of the world. Map created from several data sources including Savuta et al., 2008, Smithburn et al., 1940.

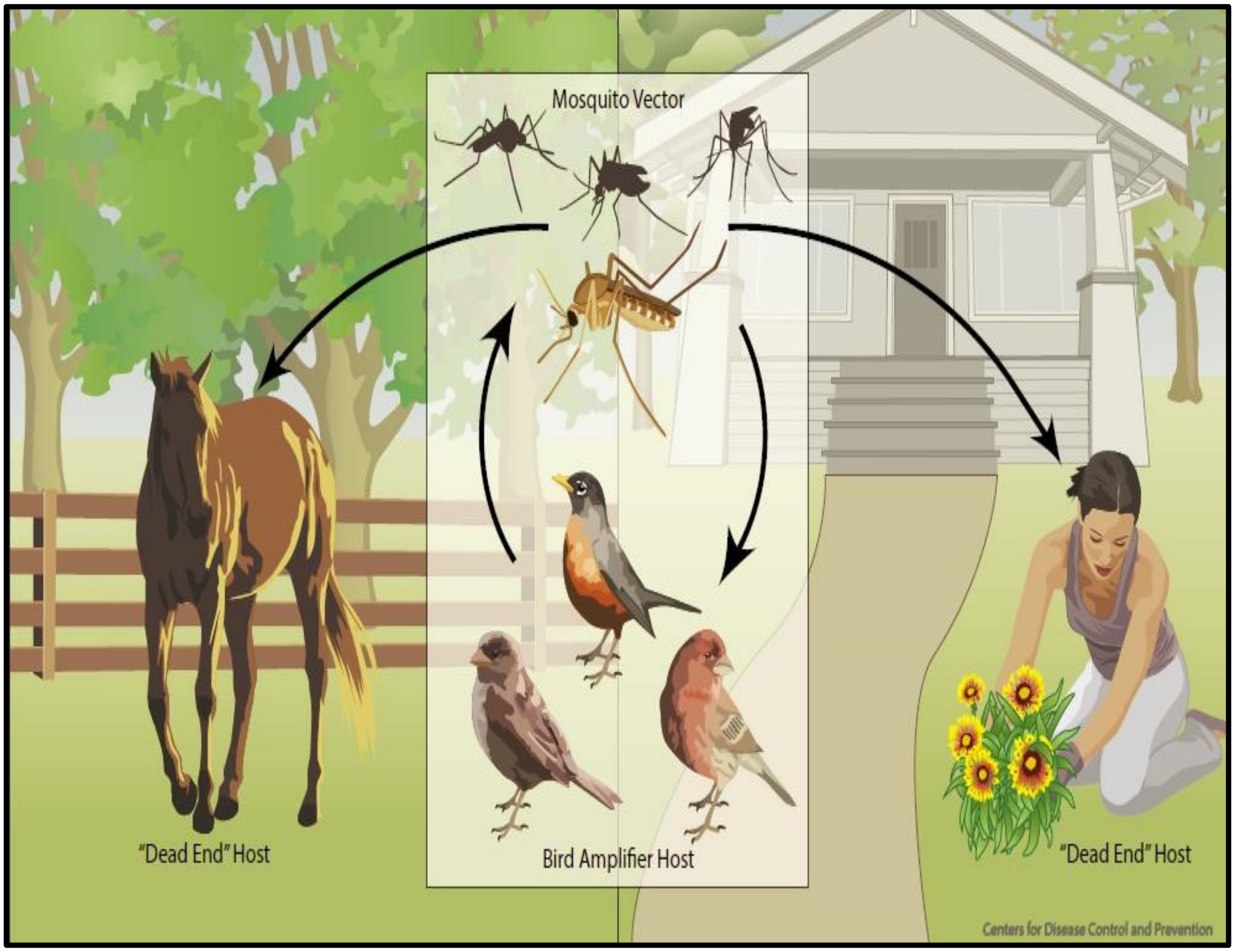


Figure 2: In nature, West Nile virus cycles between mosquitos (especially *Culex* species) and birds. Some infected birds, can develop high levels of the virus in their blood stream and mosquitos can become by biting these infected birds. Mosquitos with West Nile virus also bite and infect people, horses and other mammals. However, humans, horses and other mammals are "dead-end" hosts. This means that they do not develop high levels of virus in their bloodstream, and cannot pass the virus on to other biting mosquitos (CDC, 2013)

Figure 3: *Culex pipiens*. Primary vector and culprit of WNV transmission in Minnesota (CDC, 2013).

The primary vector responsible for disease transmission in the United States and also in Minnesota is the *Culex pipiens*, and is a blood-feeding mosquito from the family *Culicidae,* Figure 3. The disease inflames the meninges of its host creating detrimental neurologic impacts and or death. The meninges are the lining of the brain and spinal cord and therefore are immensely sensitive to inflammation from pathogenic infectious diseases such as WNV. Figure 4 is a National Institute of Health (2004) SEM image of brain tissue from an infected crow. This is a typical clinical presentation of WNV in biological subjects such as avian or human hosts. The meninges are hypersensitive to inflammation due to the biological structure of the cranium itself. The cranial vault is essentially a closed entity and allows for little change in brain size to take place. The foramen magnum at the base of the skull through which the brain stem and spinal cord are attached to the brain is the only egress for edematous tissue (accumulation of extraneous fluid in body cavities) to take. However, brain tissue forced through the foramen magnum from untreated swelling will eventually result in herniation of the brain stem and subsequent death of the individual

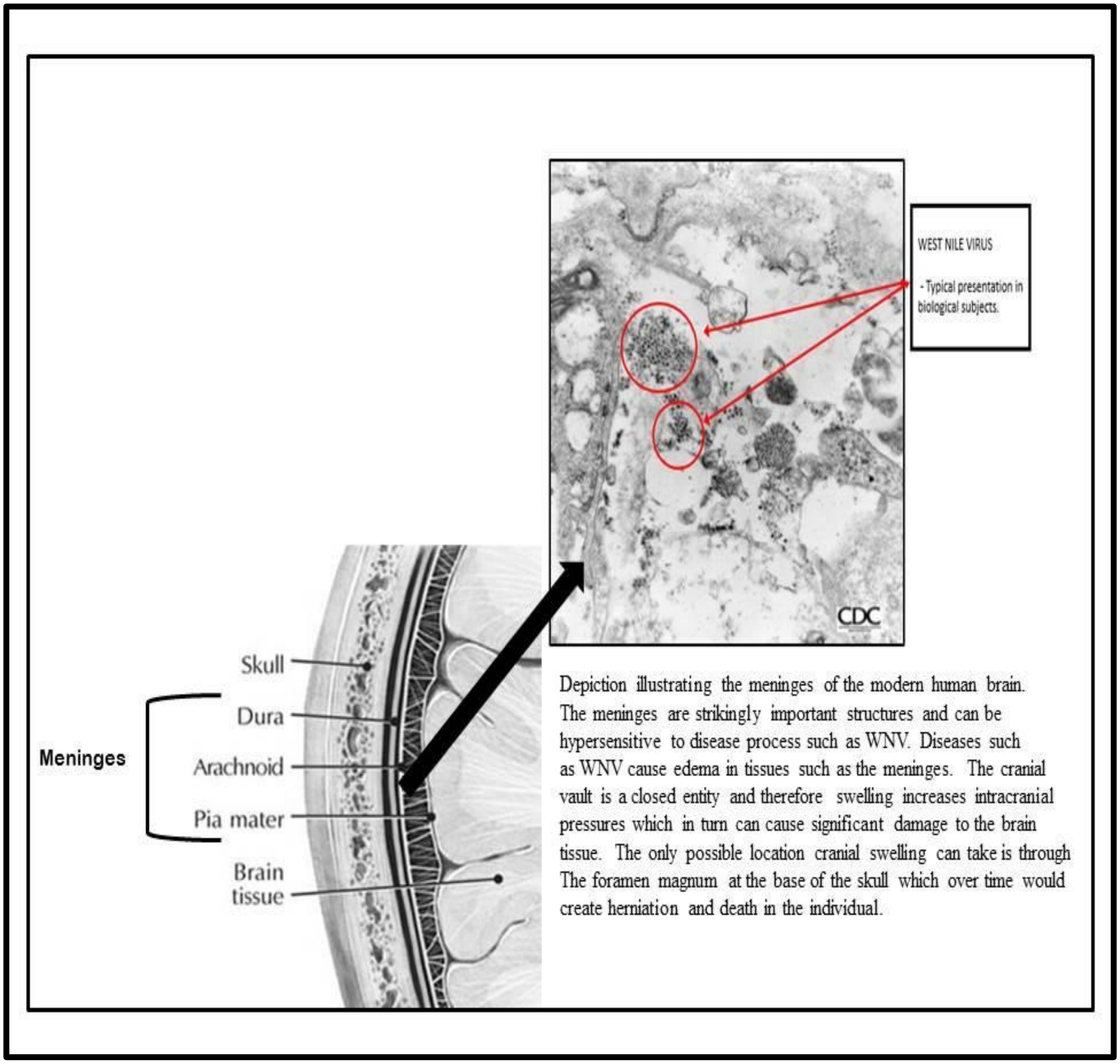


Figure 4: Meninges and typical clinical presentation of WNV in biological subjects. (NIH, 2004).

Presently, the mortality rate of WNV remains rather low on a global scale with areas of clustering outbreaks becoming more common regionally (CDC, 2013). West Nile Virus was detected in the United States in 1999 bearing a strain different from the rest of the world and was named NY099. A total of 62 reported cases in the state of New York were identified and the disease was attributed to seven deaths. Table 1 was created using data from the US CDC 2013 WNV data sets and details incidence, disease types and median age of those infected in a typical year for the US, 2012.

WNV and its propensity for prolific spread allowed the disease to reach Minnesota in a matter of three years or by the year 2002. In 2002 48 diagnosed cases appeared in Minnesota, primarily in the Twin Cities area, Upper Minnesota River and Red River Valleys. There are several factors that have the possibility of increasing the rate at which we see infected individuals being diagnosed with WNV in Minnesota. Those factors include also increased temperatures, profound drought, increased human populations and available vector habitats, increased vector populations and continued evolution and resiliency of the disease itself.

The data that will be used for analysis will come from source pools readily available to the general public on the World Wide Web. The Internet has by and large influenced and changed the course of human neuroevolution in the past two decades. Populations are accessing the World Wide Web in order to self-diagnose disease or educate themselves about their own environmental dangers that are geographically significant to their overall local and regional health.

It is the aim of this project to produce a coherent data analysis from data the general public can access, analyze and then weigh the overall risk and future risk of contracting WNV in the research area. Data readily available from reliable government or academic sources includes climate, elevation, land cover, disease and population data sets.

Attribute	US West Nile Virus (N=5,674)	
Age group (yrs)	**No. Diagnosed**	**Percent**
<18 yrs	210	4
18-59yrs	3,124	55
≥60yrs	2,340	2
Clinical manifestation		
Non-neuroinvasive	2,801	49
Neuroinvasive	2,873	51
Meningitis	1,038	18
Acute flaccid paralysis	220	4
Flaccid paralysis w/ meningitis or encephalitis	183	83
Outcome		
Hospitalization	3,491	76
Death	284	5

Table 1: N number and rate of WNV cases in the US with various attributes or characteristics to gage the diseases overall impact in 2012. Greatest areas of impact are highlighted. Data was acquired directly from the CDC open data and statistics webpage (CDC,2013). Although the mortality rate is low at 5% it is important to note that 76% of patients were hospitalized placing further pressure on the healthcare system.

II. Research Outline

The data and methods to be used in this research project will be outlined here. . The attributes to be analyzed and how they will be analyzed will be defined here as well. Different aspects of the research will be laid out including a research problem, objective, and several hypotheses will be defines by their respective elements. A mental map (figure 5) of the research is provided as well so the reader can have a sense of where this research path began and travelled.

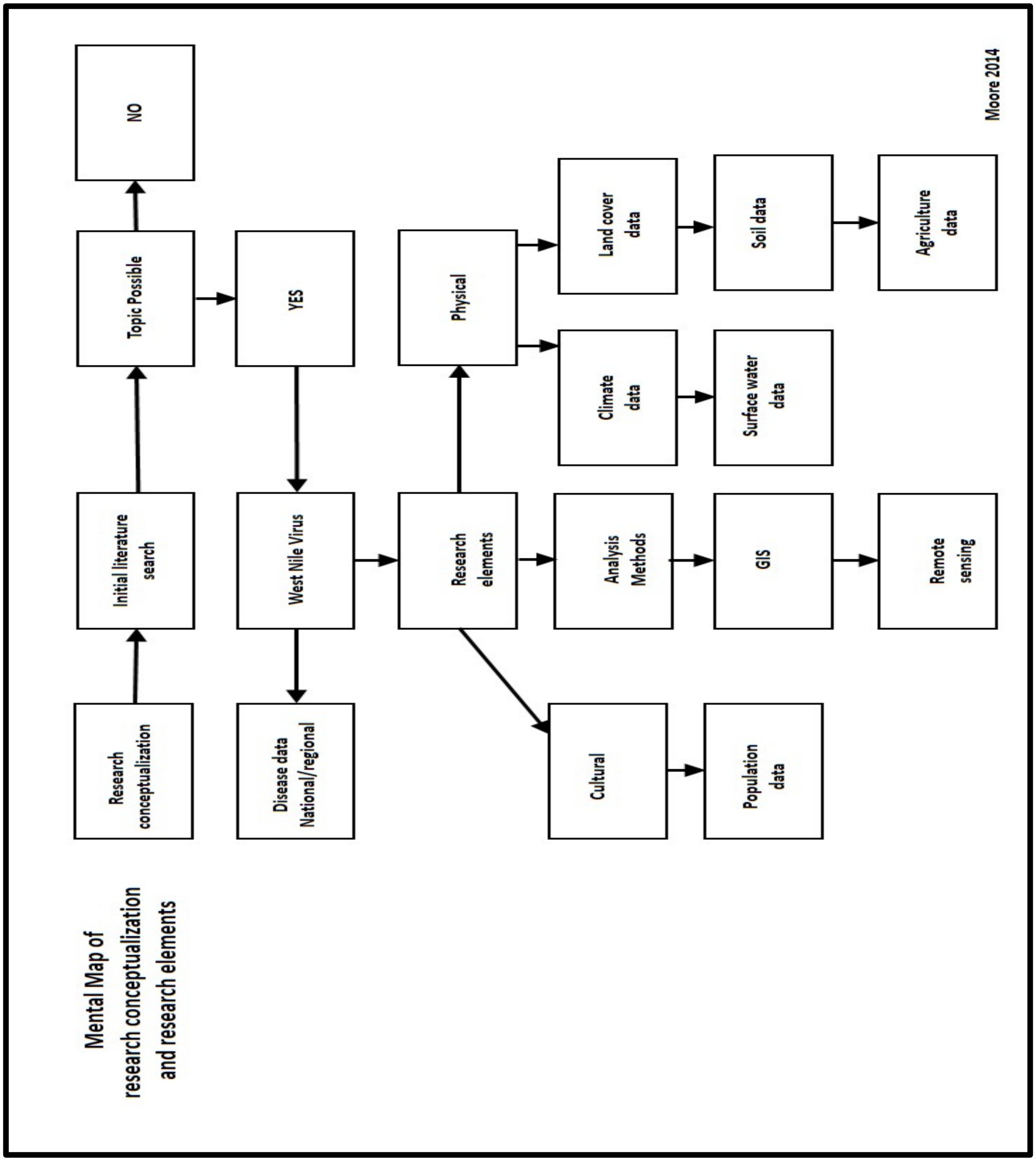


Figure 5: Mental maps are produced hundreds of times per day in humans and allow us to navigate the complex world in which we live. Mental mapping a research project can create many pathways and ideas most of which are non-useful or just not possible routes. This figure details the conceptualization and planning of this research projects with extraneous details removed.

Problem Statement

West Nile Virus (WNV) is in the family of *Flavivirus* that has the possibility of causing simple flu-like symptoms of fever, chills and fatigue and potentially fatal neurological encephalitis in human. Historically, epidemics were localized to Europe, Africa, the Middle East, and parts of Asia, and primarily caused a mild febrile illness in humans.

However, in the late 1990's, the virus became more virulent and expanded its geographical range to North America. In humans, the clinical presentation ranges from asymptomatic (approximately 80% of infections) to encephalitis/paralysis and death (less than 1% of infections) (Rossi et al, 2010). West Nile Virus is considered to be an arbovirus in that it is an arthropod-borne virus that is spread to humans by infected mosquitos (vectors). It is maintained in an enzootic cycle between birds (amplifying hosts) and ornithophilic mosquito (vectors), mainly Culex species, while humans, horses and other mammals are incidental hosts (Papa, 2013). For the purposes of this study enzootic is defined as, endemic in animals and is constantly present in the animal population but usually only infects a small number of the animal population (MerriamWebster Online, 2013). This is consistent with the pattern seen in mosquito populations. Although the disease is always present in some portion of the population non-infected mosquito pools are also present.

West Nile Virus was first isolated from a woman in the West Nile District of Uganda in 1937 (Smithburn et al, 1940). The disease is now endemic in a majority of the populations of the world including Africa, Asia, Australia, Europe and India.

In the United States West Nile Virus is one of the most recent infectious diseases to emerge and has spread within the contiguous 48 states since its introduction to New York in 1999. Figure 5 maps the spread of the WNV in three year increments across the United States. The disease was introduced in New York with a reported 62 cases and subsequently seven deaths. Following its first appearance in 1999 the virus began to spread along the eastern seaboard to Connecticut and New Jersey with 21 cases and two deaths. In 2000 the virus followed its previous track by staying in the eastern United States and specifically New York, Connecticut and New Jersey. Detection in 2001 extended into the southern states and along the entire eastern seaboard. In 2002 however an exponential increase in virus detection was reported with a total of 40 states involved accounting for 4,156 cases and 284 deaths (CDC, 2013). Following this rapid proliferation from coast to coast the disease was considered endemic with cluster outbreaks appearing and continuing to appear years later (CDC, 2013).

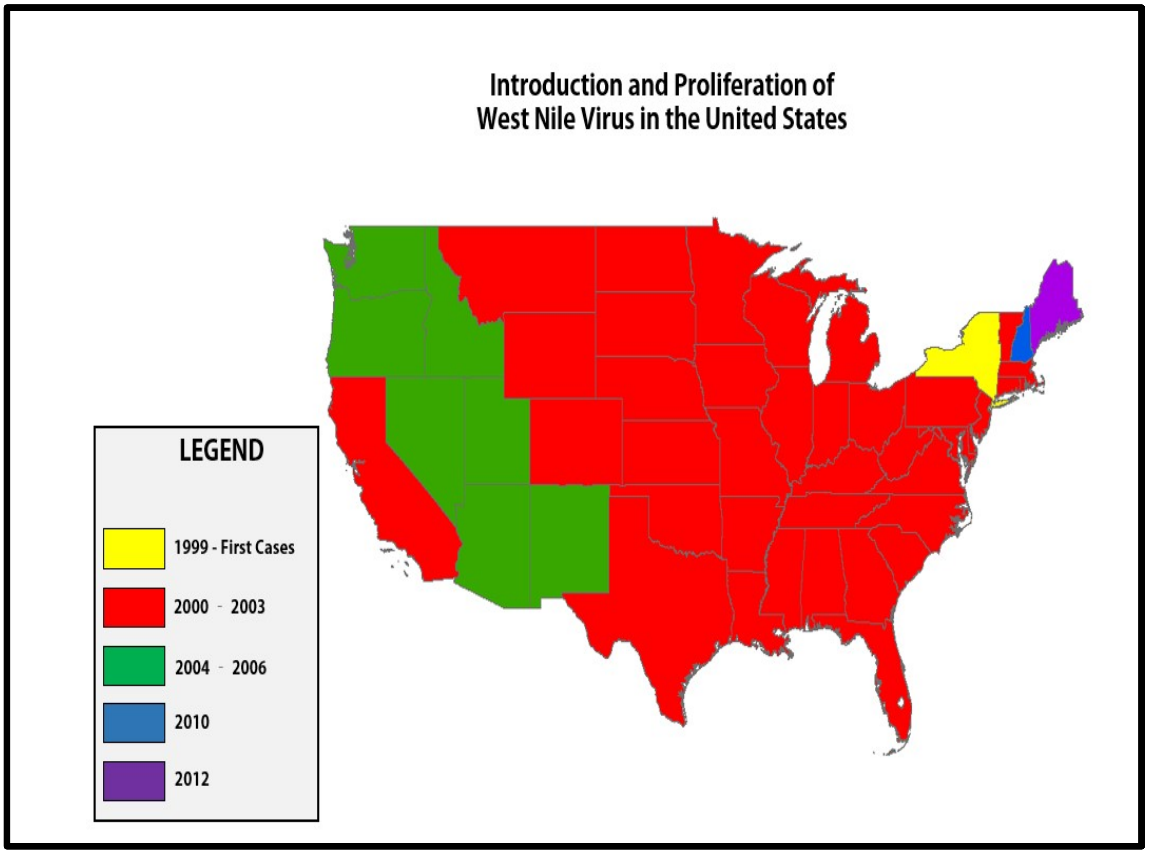


Figure 6: Proliferation of WNV across the contiguous US. The map illustrates a proliferation from coast to coast in a matter of 4 years. Minnesota appears in red as it reported its first cases in 2002.

Since its detection in 1999 WNV has continued to concern health officials due to its possibility of creating high incident clustering patterns in human populations. Large outbreaks can be seen in successive years creating increased mortality rates at a regional level (CDC, 2013). The mitigation and understanding of factors influencing this infectious disease are vital to educating and treating the persons inflicted by the virus. Continued research in many regions is therefore necessary and geospatial landscape epidemiology is a prime research discipline to better help understand the when, where and why of West Nile Virus.

Research Problem

WNV is a known and prolific disease that is capable of rapid evolutionary change as the climate changes and is the most recent arbovirus to emerge in the United States. The changing of the Earth's climate is a driver for many detrimental impacts to humans but disease has the potential to reduce population numbers exponentially with increased endemic, pandemic and epidemic level proliferations of ancient or re-emergent diseases and new unseen strains of disease (Papa, 2013). Table 2 compares and contrasts the three levels of disease in populations. The suggested change in climate with possibly less harsh winters and more warm days being available increases the possibility of disease spread and proliferation.

TYPE	*CHARACTERISTICS*	*Specific to WNV*
Endemic	Growing or existing in a certain place or region.	WNV exists in Minnesota and cases are expanding.
Pandemic	Occurring over a wide geographic area and affecting a large portion of the population.	WNV exhibits characteristic cluster outbreaks affecting high percentages of resident populations.
Epidemic	Affecting or tending to affect a disproportionately large portion of the population, community or region at the same time.	Although this is not common in the US small villages in Africa have had WNV epidemic outbreaks impacting all or a large percentage of the resident village populations.
Data source	Merriam-Webster Online, 2013	CDC, 2013

Table 2: Comparison of three levels of disease in populations. Each is defined by a universally accepted definition and is then used in a specific WNV scenario.

In Greer (2008) three transmission links are outlined and relevant to the study area.

The risk of transmission of pathogenic agents by mosquitoes is not linked to their mere presence but to:

1. Vector competence (ability to complete the cycle of the pathogenic agent within the vector, followed by transmission);

2. Meteorological conditions enabling:
    a. The pathogen to complete its extrinsic cycle during the vector's period of activity;
    b. The vectors to be active and abundant enough (with the role of environmental conditions);
3. The presence of the pathogen and of at least one reservoir.

All points are vitally relevant to the spread and continued virulence of WNV in Minnesota and will be addressed in this thesis using the various remote sensing, GIS, and statistical data that are readily available online to the public.

Research Objective

The research objective of this thesis is to evaluate the incidence of WNV in the Upper Minnesota River Valley and to explore human/environmental factors that contribute to the spread of the disease. The identification of factors that influence the spread of WNV will enable public health departments to better develop monitoring systems and prevention strategies. Emerging or invading arboviruses may amplify to epidemic levels because natural systems have been perturbed by changes in viral genetics, host or vector population composition or dynamics, and/or environmental structures that frequently are of anthropogenic origin (Weaver and Reisen, 2010).

III. Research variables

Following an in depth analysis of the literature many questions concerning the spatial patterns of WNV can be raised. Each set of variables are broken into specific factors to be tested. The factors and data to be analyzed include physical geographic data such as climate, land cover, soil and elevation; confirmed human WNV cases from the years 2002-2012; climate data involving precipitation and temperature.

The first factor to be assessed is the confirmed number and spatial pattern of WNV from the years 2002-2012 in Minnesota.

Spatial distribution

The spatial distribution of WNV is random in the Upper Minnesota River Valley.

The spatial distribution of WNV is significantly clustered in the Upper Minnesota River Valley.

Physical environment

The second set of factors to be tested involves the physical geography of Minnesota. The literature review indicates that arboviral infectious disease is significantly impacted by the physical environment. The impact of the physical environment can constrain or enable diffusion of the disease (Weaver and Reisen, 2010).

This set of factors will analyze the relationship of confirmed WNV cases with the physical environment characteristics. This will help to establish a pattern of acceptable vector habitat locations in the study area.

Soil

The type of soil has an impact on the spatial distribution of WNV.

The type of soil does not have an impact on the spatial distribution of WNV.

Climate

Increased precipitation does not increase the occurrence of WNV.

Increased precipitation does increase the occurrence of WNV.

An increased number of days above 50^0 F in March does not increase the occurrence of WNV.

An increased number of days above 50^0 F in March does increase the occurrence of WNV.

Agricultural patterns

The percentage of cultivated land does not impact the spatial distribution of WNV.

The percentage of cultivated land does impact the spatial distribution of WNV.

Water

A higher percentage of water bodies (lakes and wetlands) does not have an impact on the spatial distribution of WNV.

A higher percentage of water bodies (lakes and wetlands) does have an impact on the spatial distribution of WNV.

Urban

The last factors to be analyzed will be that of urban geographies involving populations. The literature review revealed that WNV seems to cluster more significantly in higher populated urban centers (Oldstone, 1998). This set of hypotheses will be evaluated at county level as well by mapping total population and urban population centers.

Population: county level

A higher population does not influence the spatial distribution of WNV.

A higher population does influence the spatial distribution of WNV.

IV. Methods and Data

Many methods have been used to study the pattern and expansion of disease in human populations of the world. Understanding the spatial scale and temporal pattern of disease incidence is a fundamental prerequisite for the development of appropriate management and intervention strategies. It is particularly critical, given the need to understand the elevated risks linked to climate change, to allow the most likely changes in the distribution of parasites and disease vectors to be predicted under a range of climate change scenarios (Rose and Wall, 2011). The methods to be employed in this thesis will involve acquiring remotely sensed data such as aerial photography and Minnesota Geospatial Information Service LiDAR (Light Detection and Ranging) data. Additional data will be derived from Minnesota Meteorological Center climate data, National land cover data, hydrology data, and United States Census Bureau population data, Center for Disease Control and Minnesota Department of Health WNV data. All resources are available on the World Wide Web.

The data will be analyzed using various methods including spatial, statistical and trend analysis. The applications that will be used will be ArcMap 10.1, Adobe illustrator. As with any study other unforeseen methods will be utilized as well. Table 3 provides a summary the remotely sensed and physical data to be assessed.

Table 3: Remotely sensed and physical data to be used.

Data	Technique	Expected result
SSURGO soil data	ArcMap 10.1	Mapped hotspots of poor permeability and soils at risk. The error in this data set is considered to be high. Last collection date of soil data was 1999.
Lake density/ surface water percentage	ArcMap 10.1	Mapped density per county. Higher volume percentage indicates higher likely disease numbers. A standard error of 2.5-5% is expected in amount.
Agricultural density	ArcMap 10.1	Mapped density per county. agriculture v. uncultivated land percentage. Error will exist due to mixed pixel value/types.
Wetland percentages	ArcMap 10.1	Wetlands are harbingers of vector populations and important factors in reservoir pools.
Climate (temperature) data	Evaluation of climatic factors over a six month span for years 2002-2012.	Increased number of warm breeding available days. Increased number of warm days extending biting (transmission) cycle.
Climate (precipitation) data	Evaluation of precipitation data for years 2002-2012.	Increased rainfall producing and increase in standing water locations. More breeding pools available.
Aerial Photography mosaics (geo or orthorectified)	Repeat imagery, comparison of land covers, water abundance, and human impact. ArcMap 10.1	Increased mosquito (vector) habitat availability.
LiDAR (Light and Ranging Detection)	ArcMap 10.1 elevation analysis	Lower areas in elevation can create more ponding and stagnant water locations, vector habitat.

Expected results

I expected that WNV will continue its increased occurrence within the human population of Minnesota. It is also expected that land cover, climate and population change/expansion will be the overriding factors influencing the increased prevalence. These changes will allow modeling scenarios to be produced that will allow for future possible impacts to be outlined. The overall data analysis will allow a comprehensive and in-depth geographical picture to be seen by others concerned with this health issue.

V. Research significance

The continued presence and increase in WNV incidents indicates that the disease has become endemic in the United States. Endemic diseases that are relatively new to an area warrant intense research however little research has been completed in the United States that addresses the factors in this thesis. Much work has been completed in Europe addressing similar factors such as climate, population and land cover changes allowing for a template to be built to address WNV in Minnesota. Minnesota has seen years with little disease detection to years of high disease rates that may be attributed to things such as climate and land cover changes. The data will be weighted on a county level which will allow areas of concern to be identified.

Evaluating these factors can allow for the better implementation of monitoring and mitigation techniques.

Chapter Two

Medical Geographic Methods and Diffusion Theory

I. Introduction

This chapter intends to examine the concepts and previous work done in the fields of medical geography, geographic analysis using geographic information systems, remote sensing, and diffusion theory. All of these techniques and methods play an important role in allowing humans to better understand the environment in which we live and the disease dangers we face throughout our lives.

Medical geography has gone though many phases and has been recognized since the 5th century as an important factor in overall human health. The impacts that our local environment has on our populations can be devastating and can also go undetected for quite some time. Humans play a large role in the environments in which we live. Simply because the modern human creates, inhabits and impacts their environment far more than our predecessors and much of that impact is detrimental to self and surroundings.

History of Medical Geography and Major Contributors

Medical geography is a research discipline that is considered one of the human or cultural geography sub-specialties in the academic realm. The interaction of humans with their environment is something that happens to all populations on a daily basis. The environment provides many necessary things for humans but it can also bring populations into contact with disease and disease causing organisms.

Medical geography is a relatively new term in the field of geography when placed in the context of human existence. The practice of using geography and place to understand disease can be found as far back as Hippocrates, c. 460-370 B.P. It has been known for thousands of years, at least since the time of Hippocrates, that climate has wide ranging impacts on health (Haines et al, 2006). The discipline has grown immensely as human evolution and technology has advanced. In antiquity three physicians laid the groundwork for much of the medical geographic research being done in contemporary America. The three individuals to be examined and will best detail the history of medical geography are John Snow, William Farr and Daniel Drake. Their contributions, previous work from Europe and the industrialization of the United States laid a strong base for the techniques being used in this research discipline today.

Major Contributors

John Snow

While in the throes of multiple epidemics one physician made an impact with an applied medical geographic approach that influenced environmental medicine theory that is still useful today.

John Snow was an English physician who practiced in London during the middle 1800's and became integral in identifying the causal factors of the second cholera epidemic. During this early phase in medicine the cause of cholera was effectively unknown and the assumption was that it was a blood borne affliction.

Snow was convinced that the disease was transmitted via other more common factors. He believed that it was spread in the water and was digestive in nature. He published a pamphlet speculating that cholera must be, fundamentally, a digestive disease, because the initial symptoms were vomiting and diarrhea. This premise led Snow to conclude that the contagion entered and left the body through the oral-fecal route, and therefore that cholera was caused by consuming a contaminated substance. His argument contradicted the multitude of doctors who believed that cholera was essentially a disorder of the blood (McLeod, 2000).

The second London cholera outbreak occurred in 1854 and was described by John Snow as, ''the most terrible outbreak of cholera which ever occurred in this kingdom'' (Snow, 1855a: 38). However, this outbreak gave Snow the chance to test his radical theory. During a reported ten day period in late summer the outbreak took over 500 individual lives.

Dr. John Snow used a dot-map showing the location of cholera deaths to identify the source of the outbreak as the Broad Street community water pump. Figure 7 is a map recreation from "Snow on Cholera" by WH Frost, 1936 the map illustrates the applied medical geographic technique Snow utilized, which defined the cause being the Broad Street pump. He convinced the Board of Guardians that the pump should be deactivated, they removed the handle, and the number of deaths dropped immediately.

His research helped to change his contemporaries' theory of disease transmission (McLeod, 2000).

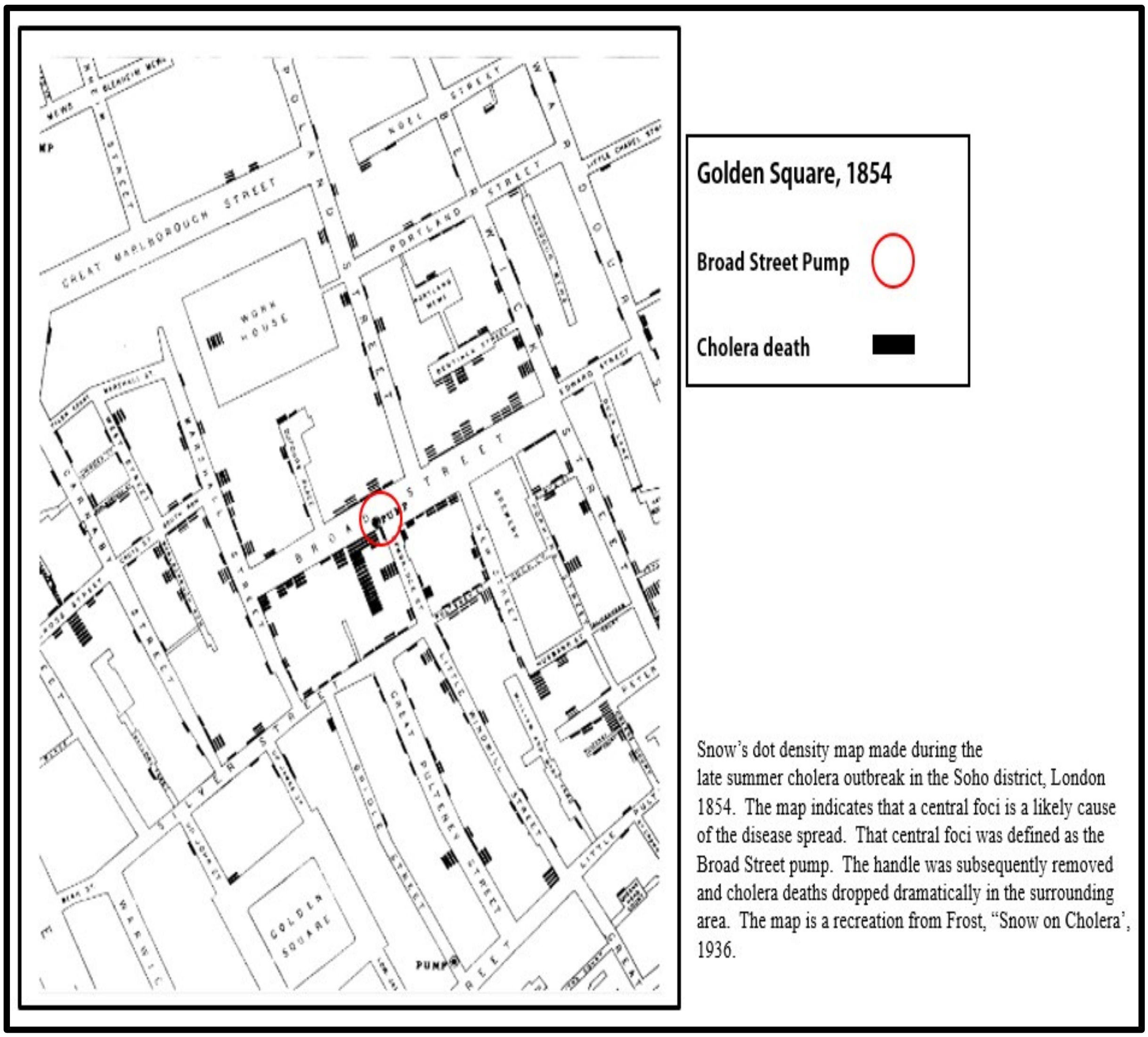


Figure 7: Digital reproduction of John Snow's dot density map. Map reproduced from McLeod 2000.

William Farr

The impact climate has on human health is not a new concept in the environmental science and medical geographic fields. William Farr was an 1800's epidemiologist that recognized the impact climate has on human health and equated the cholera outbreaks in England to these phenomena (Farr, 1852). His approach was based on population surveillance and statistics which was a step in the direction of modern environmental medicine. Elected a fellow of the Statistical Society in 1839, Farr described statistics as a "master science" permitting elements contributing to disease to be discovered and "natural laws" of health and disease to be formulated (Koch, 2011). Farr subscribed to the accepted theory of the day in the 1800's, miasma theory.

In miasma theory, diseases were caused by their presence in the air of a *miasma*, a poisonous vapor in which were suspended particles of decaying matter that was characterized by its foul smell (Science Museum U.K.) . The theory originated in the Middle Ages and endured for several centuries despite its inadequate ability to explain causes of disease in a scientific and fact based way. Farr (1852) produced a statistical coxcomb graph that detailed the influence climate had on cholera between the years 1840-1850. This approach was considered innovative for the era and yet as a result graphing and statistical analysis is a standard approach to presenting geographic data in modern research. Figure 8 is a digital reproduction from the British Museum, UK of Farr's coxcomb graph.

Figure 8: The graph effectively compares average mortality from cholera and average temperature. In detail the radii of the circle represented weeks of the year; the concentric circles in each year symbolized gradients of either 10 degrees of temperature or 100 deaths, depending on their function. Black extrusions outside the circle marked periods of excessive mortality, yellow figures inside the circles periods of diminished mortality (Koch, 2011).

In addition to using climate as a proxy for explaining the occurrence of disease Farr also produced studies involving elevation, soil and air quality data. Many of these are not applicable in a host of diseases but in the case of WNV it has been shown in previous studies that soil and elevation do play a role in the incidents and therefore will be examined in this thesis. Figure 9 is a digital reproduction of Farr's diagram detailing the relationship between elevation and cholera. The diagram represented an inverse relationship between cholera and altitude above sea level in England. Farr presented both the data and his conclusion based upon it without sacrificing the real complexity of the disease as an environmental, social and temporal thing (Koch, 2011).

Many of the attributes used by William Farr to better explain cholera and its diffusion are certainly relevant to the study of WNV. Climate (temperature and precipitation) play a large role in the vector being able to complete the transmission cycle to humans. Elevation plays its part as well as habitats are known to change with elevation and this will impact vector abundance. Soil is also possible a causal factor as well drained soils allow little vector habitat to be present. Poorly-drained soil will allow for ponding and stagnation of water creating an ideal location for vector breeding to take place.

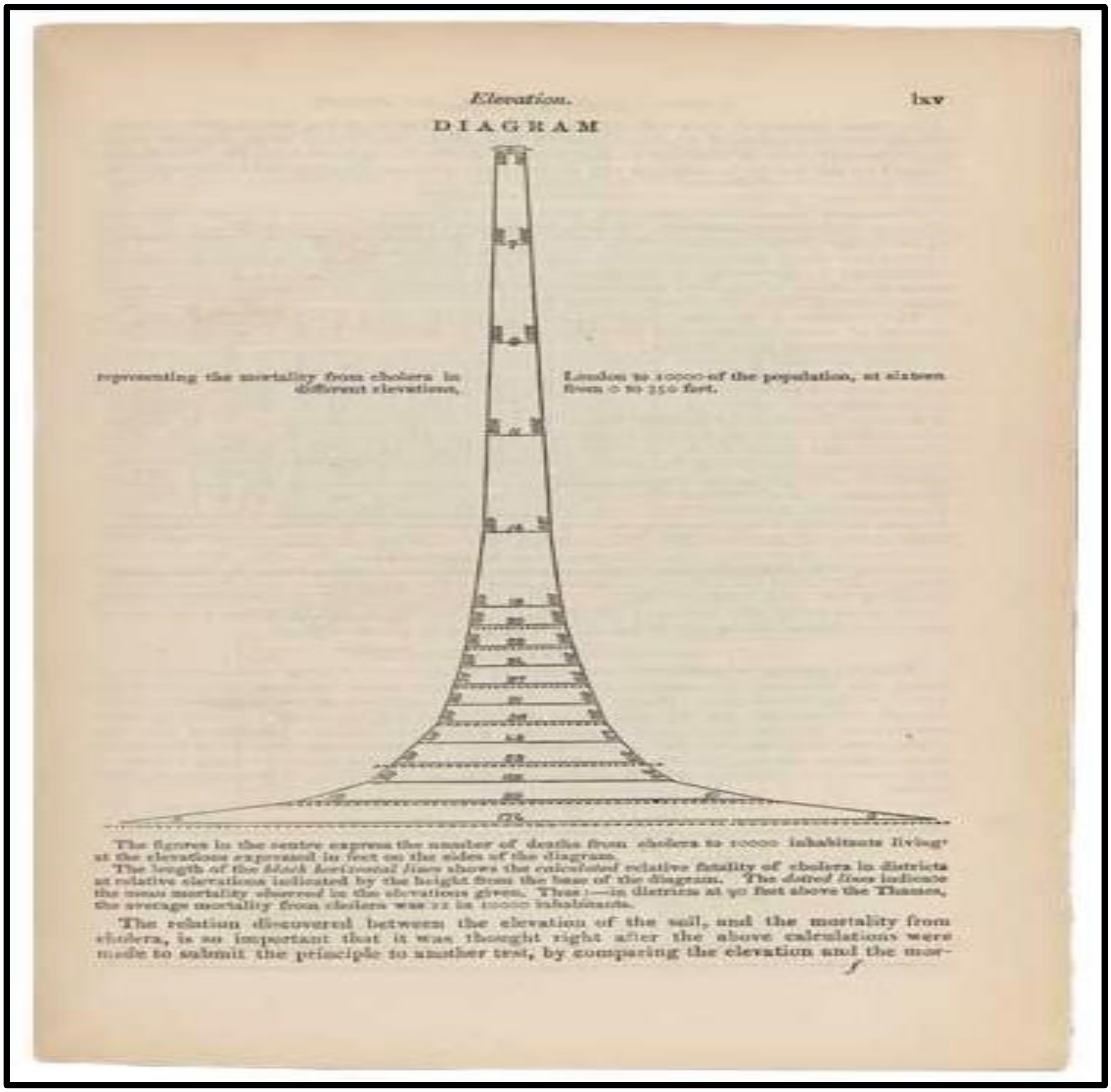


Figure 9: Farr's Report offers some exceptional visual explanations of cholera mortality data. Contrary to Snow, Farr's analysis was leading him to the conclusion that elevation above sea level was the key factor in the communication of cholera. Whilst his diagram clearly how's the relationship between lower ground elevation and higher mortality, this association was due to differences in water sources in these locations. It is a reminder of how visualizations containing false associations have the power to mislead us. Diagram originally published by Farr in, Report on the Mortality of Cholera in England, 1848-1849. Image accessed thru the Wellcome Library, London. Wellcome images.

Daniel Drake

Daniel Drake was the progeny of a simple Kentucky frontier family who lived between the years 1785-1852. Drake grew up on the frontier and never acquired any formal medical school training but he did study under the only physician in the area, who considered him "graduated" after five years of work. In fact Drake is generally believed to be the first person to qualify as a physician west of the Allegheny Mountains (Horine, 1961). His work and contributions to the field of medical geography were significant in a time when nearly all medical geographic work was being done in Europe. Although Drake was a physician wanting to resolve medical problems the approach he took was a geographical one (Barrett, 1996). He published one major volume of work that laid the foundation for further medical geographic research in the United States. The work that he published was entitled "*Principal Diseases of the Interior Valley of North America*", In 1850. Drake's contribution appears to have occurred largely independent of the European literature. Certainly, in its method, no one up to that point had developed such a detailed approach for so vast an area about the relationships between geography and disease (Barrett, 1996).

II. Geographic Analysis: Remote Sensing and GIS

A geographic information system (GIS) integrates hardware, software, and data for capturing, managing, analyzing, and displaying all forms of geographically referenced information.

GIS allows us to view, understand, question, interpret, and visualize data in many ways that reveal relationships, patterns, and trends in the form of maps, globes, reports, and charts (ESRI, 2014). This technology allows us to gain a unique insight into the patterns of disease and present those findings in a cartographically pleasing way. The classical tool for visualizing spatial information on disease spread is a geographic information system (GIS) (Ramirez-Ramirez et al, 2013).

Remote sensing can be defined several ways and many definitions have been proposed. Remote sensing is the science of obtaining information about objects or areas from a distance, typically from aircraft or satellites (NOAA, 2014). Remote sensors collect data by detecting the energy that is reflected or omitted from Earth. These sensors can be on satellites or mounted on aircraft. Remote sensors can be either passive or active. Passive sensors respond to external stimuli. They record radiation that is reflected from Earth's surface, usually from the sun. Because of this, passive sensors can only be used to collect data during daylight hours. In contrast, active sensors use internal stimuli to collect data about Earth. For example, a laser-beam remote sensing system projects a laser onto the surface of Earth and measures the time that it takes for the laser to reflect back to its sensor (NOAA, 2014).

The United States has a myriad of remote sensing programs and applications in use today. Presently, the largest application is by the National Aeronautics Space Agency (NASA) who has 27 missions operating as of March 2014. Each mission has a specific task and each mission also has specific parameters for type (land, water, atmosphere), location (geostationary, roving, height), temporal cycles (days a location is revisited) and spatial resolution (NASA, 2014).

For the purposes of this research it was found that aerial imagery on an airplane platform and radar based missions were best suited. Aerial imagery allows you a large span of time and space to discern land cover changes and anomalies. Radar based technologies such as LiDAR (Light and Range Detection) allows for clear unobstructed (no clouds) data sets to be utilized.

III. Diffusion Theory

One of the basic components of studying disease in the human populations is how a specific disease moves or diffuses through the resident populations. Learning the spatial characteristics of disease helps to better understand factors influencing its geographic distributions. This was seen in the work of Dr. John Snow and the diffusion of cholera through the population in Golden Square, London. The most often used method to study this movement is known as diffusion theory which uses methods to study the spatial diffusion of disease in populations. The research focus in this paper entails establishing and analyzing spatial attributes, patterns and environmental factors that are or are not influencing the prevalence of WNV within the study area.

Diffusion theory is most often referred to as spatial diffusion and entails several basic elements. The theory was developed initially to explain the spread of innovation and or knowledge. It was Gabriel Tarde in his *Laws of Imitation* (Tarde, 1903) who, first argued that proximity led to imitation, and that imitation occurred through a trickle-down process, whereby “inferiors” imitated “superiors” (Brown, 1968). Tarde also described the S-shaped or epidemic curve that characterizes the cumulative rate of adoption.

The curve increases slowly at first, then rises rapidly, and naturally slows down and levels off. In many cases, discontinuance occurs, and the decrease follows a similar pattern to the increase. This S-shaped curve is what is seen as disease invades a geographic location, proliferates and subsides.

What is ultimately seen is a period of high incidence followed by a plateau of confirmed cases and ultimately a decrease in case presentation over time (Ferrence, 2001).

An accepted process for environmentally based research was proposed by Brown in 1969. The process detailed six basic elements: origin, destination, relationship between origin and destination, environment or area of importance, time, and item being diffused (Brown, 1968).

Brown, 1968 additionally breaks the process down into three different groups in relation to populations impacted. These groups are susceptible populations, removal populations and infective populations and these are mostly relevant in the study of WNV. A limiting factor will be infectives and this will be discussed in a later chapter. Susceptible population are those that do not have the innovation (or disease) but are able to receive it. For this study that most often involves the very young (<5 years) and the elderly (>62 years) of the resident populations.

Removals are those that have had the innovation (disease) and are not able to pass it on. Humans are considered to be dead-end hosts in the WNV transmission cycle however that entails only direct transmission. Indirect transmission is documented extensively where WNV is passed from blood donor to recipient.

In order for the innovation or disease or pathogen to be able to diffuse, there have to be enough susceptibles and infectives available (Brown, 1968).

The destination is the geographic location that the innovation or disease invades, a new not formerly inhabited location. This area must contain a sufficiently sized susceptible population and in the case of WNV that typically involves all of the resident population as no "immunity" is known to exist in humans. Destination is usually linked to, or similar to, the origin. This could be similar in environment, social or economic characteristics. There must also be little resistance in the destination area or the disease or pathogen will not survive (Brown, 1968).

The environment in which the innovation or disease invades can play the largest role in it success or demise. The terrestrial, climatic and cultural aspects of an area typically play the largest role in disease prevalence and are the most evaluated attributes. These features shape the diffusion process due to the influence of barriers (Abler, Adams, and Gould, 1971). The research of Abler, Adams and Gould defined three barrier types: absorbing, reflecting and permeable barriers. Absorbing barriers are capable of stopping the diffusion process. This can be seen in vicariate barriers such as mountains or in isolated populations. Reflecting barriers typically deflect the disease back to its origin or in another direction. This barrier allows for amplification to become evident in populations. The permeable barrier is one that will not stop or deflect the disease. This is the typical pattern seen in WNV as the disease seems to simply pass from one population to the next. The item or phenomenon being diffused can be diverse, including ideas, innovation or disease pathogens.

Depending on the nature of the item, the process will be different (Brown, 1968). Time is an important factor in the diffusion theory model and in many cases is the overriding influential factor. Diffusion has been described as having three distinct stages in respect to time. The primary stage, or colonization, during which the item being diffused will enter a new area. The second stage is the actual diffusion or spread of the item. The final stage takes place when the item being diffused finally slows down due to saturation or when the removal rate is greater than the infection rate (Brown, 1968).

There are four distinct types of diffusion processes that can be outlined. They consist of expansion diffusion, contagion diffusion, relocation diffusion and hierarchical diffusion. The diffusion process is not particular in that more than one diffusion process can be taking place in a location at the same time (Abler, Adams, and Gould, 1971).

Expansion diffusion typically exhibits a constant rate as it spreads through the population. The total number of the population that has received the item increases with time. The contagion diffusion has similar characteristics to expansion diffusion. Contagious diffusion is sometimes related to expansion diffusion, because the item is technically expanding (Abler, Adams, and Gould, 1971). Contagious diffusion is typical with infectious disease, a well-studied example would be annual influenza spread in the United States. Typically one person spreads the contagion to other susceptibles and over time the contagion spreads through the population. Relocation diffusion is the process by which the pathogen relocates to a completely different location. This diffusion is intimately linked with transportation and migration factors and therefore is important in the study of human diseases.

The main host in WNV is avian in nature and relocation and subsequent diffusion of the virus to new areas is common. Diffusion and the factors impacting the spread, time and number infected can be a complicated and complex problem. Changes in the cultural and physical environments of a location play an important role in the diffusion process. Factors such as population changes, climate and even topographical changes can influence the spread of disease in populations.

Chapter Three

The Human and Physical Geography of Minnesota

I. Introduction

Minnesota is a state that was inhabited by large indigenous Native American populations for hundreds of years prior to European settlement. The state became the Minnesota Territory in 1849 and a legal part of the United States in 1858 (Blegen, 1975). The area was renowned for its lakes, timber and furs that drove the early economy in the state. Iron mining and farming also brought large numbers of European settlers following its acceptance into the United States. The area was fraught with Native American and European clashes with the Dakota War of 1862 being a tragic highlight in the states young existence (usdakotawar.org). Minnesota exhibits a diverse topography that was shaped by multiple glacial pulses and lobes. The state abounds with high latitude grasslands, deciduous and conifer biomes, moraines, eskers and a multitude of lakes and rivers.

This chapter will describe the human and physical properties that lie within the state that essentially impact the prevalence of WNV. The cultural areas to be examined are population geographies including ethnicities, densities and distributions of populations within the study region. Physical geographies such as climate and land use will also be addressed as these directly impact the nature, distribution and future prevalence of WNV in Minnesota. Making a complete assessment of all these factors allows for an in-depth and objective analysis of WNV to be produced.

II. Population Geography

Today, the state of Minnesota is inhabited by mixed cultural populations that reside in a few large metropolitan locations and many small and mid-sized rural towns. The largest population center is centered on the Minneapolis/Saint Paul seven-county metropolitan area and typically reports the highest incidents of WNV yearly. The United States Census Bureau reports Minnesota having a resident population of 5,303,925 and an average of 66 persons per square mile following the 2010 census (US Census Bureau, 2010). Table 4 a, b, c, d defines aspects directly related to the population residing in Minnesota. The characteristics outlined are total population, ethnicities, age ranges, gender percentage, total and percent change in population from the last two census polls in the years 2000 and 2010. Data for table 4 was acquired from American Factfinder, provided by the US Census Bureau. The data is of public record due to the Freedom of Information Act (FOIA) enacted on 4 July 1966
(US Census Bureau/FOIA, 2014).

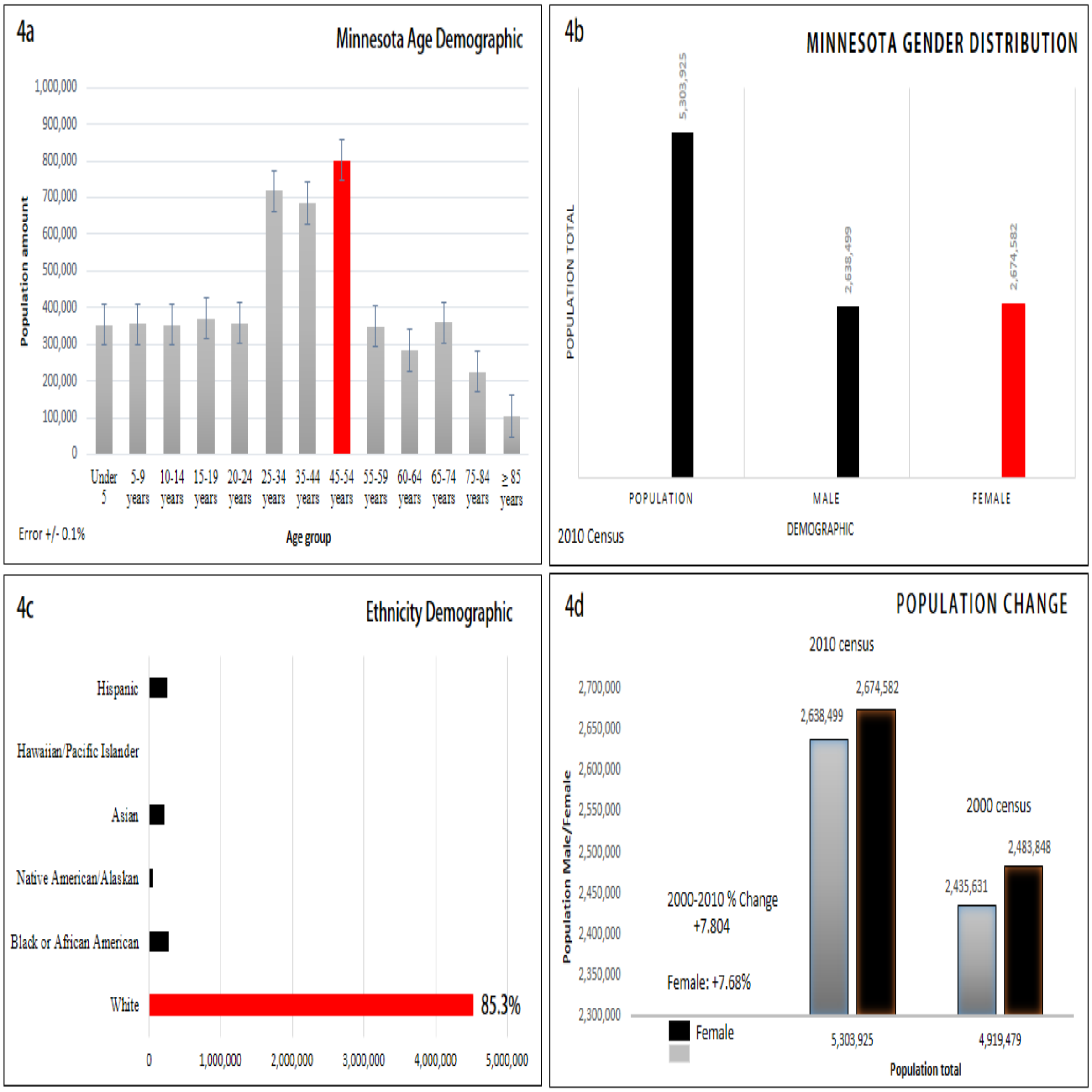


Table 4a: Age demographic within Minnesota, 45-54 years of age. 4b: Minnesota gender distribution. Red indicates largest total gender, female. 4c: Ethnic demographic. Red indicates largest demographic, white. 4d: illustrates the change in population between census 2000 and census 2010. Data obtained from American Factfinder 2010 census webpage (US Census Bureau, 2010).

The study area contains 18,192km^2 of land surface spread over 10 separate jurisdictional counties in the Upper Minnesota River Valley. Figure 10 is a GIS derived map that outlines population densities by county in the study area.

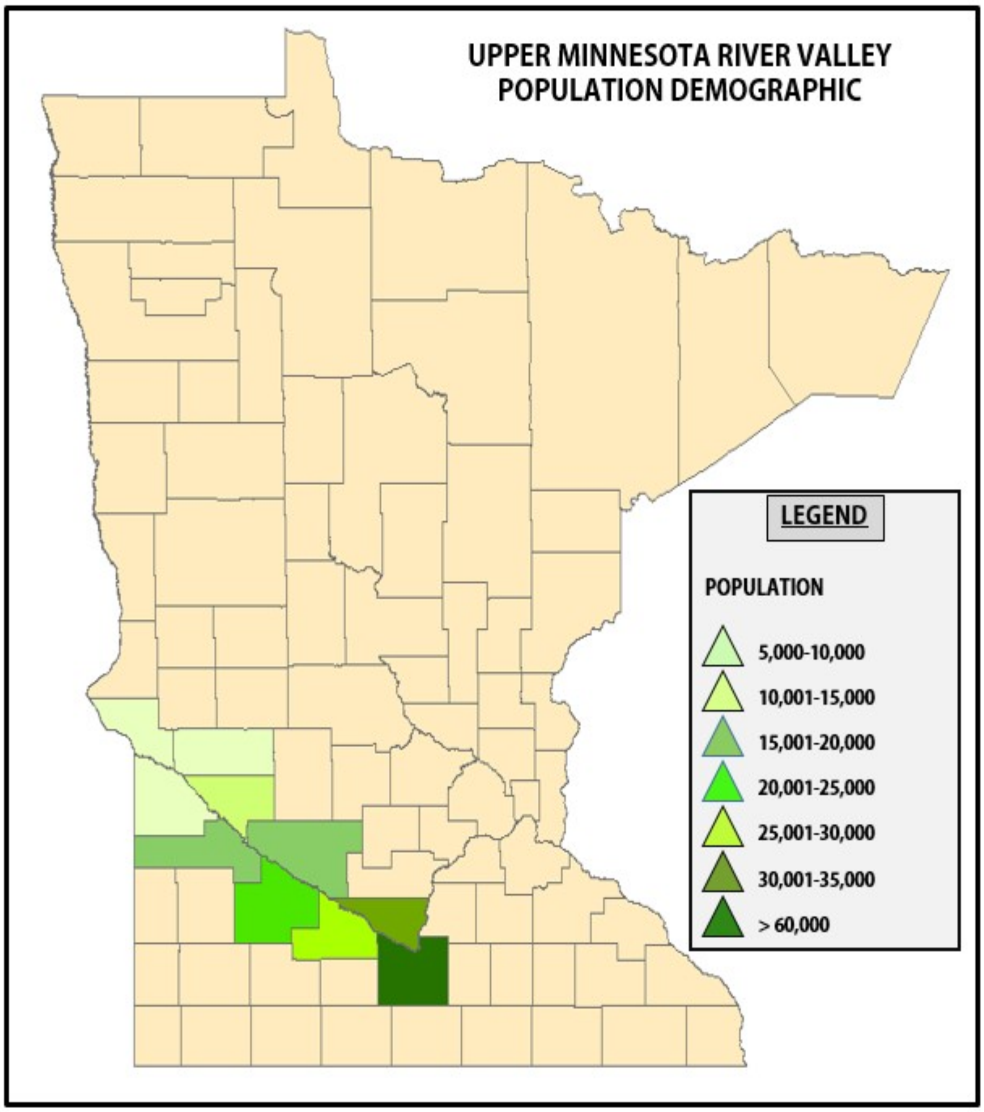


Figure 10: GIS derived map detailing population per county. Data used for map creation is from United States Census Bureau, American Factfinder (US Census Bureau, 2010).

III. Climate

Climate, weather and disease are intimately intertwined in an elegant, dynamic and complex dance that is becoming increasingly more evident in today's world. Climate constrains the range of infectious diseases, while weather affects the timing and intensity of outbreaks. A long-term warming trend is encouraging the geographic expansion of several important infections, while extreme weather events are spawning 'clusters' of disease outbreaks and sparking a series of 'surprises' (Epstein, 2001). The impact climate has on human health is not a new concept in the environmental sciences field. William Farr was a mid- 1800's Epidemiologist that recognized the impact climate had on human health and equated the cholera outbreaks in England to this phenomena. His approach was based on population surveillance and statistics which was a step in the direction of modern environmental medicine.

Arthropod or vector-borne diseases such as WNV are increasing in prevalence from the present climatic shift we are now experiencing here on the planet Earth. The recent release of the Intergovernmental Panel on Climate Change's (IPCC) fifth assessment makes a bold statement that directly attributes nearly complete responsibility for the noticeable shifting climate to anthropogenic impacts. Human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes.

It is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century (IPCC fifth assessment, 2013 WG 1 and 2014 WG 11).

The Köppen Climate Classification system is a universally accepted system that was developed by Russian Climatologist Wladimir Köppen in in 1884. Minnesota has a unique location in that it lies within two distinct zones of the Köppen climate system. The climate is typical continental with hot/warm humid summers and traditionally excessively cold winters. The state within two Köppen climate zones is broken into the northern part (from ~ Minneapolis/St. Paul north) being placed in the Dfb (cold, without dry season, *warm* summer) climate zone and the southern part located in the Dfa (cold, without dry season, *hot* summer) climate zone. Figure 11 illustrates the Köppen World Climate Map; the continental United States is highlighted to illustrate the study location of Minnesota. The two parts of the state are essentially the same except that the northern part is in the cold, without dry season, *warm* summer climate and the southern part is in the cold, without dry season, *hot* summer climate (Peel, Finlayson, McMahon, 2007). Although the difference is somewhat minimal it can influence the prevalence of environmental diseases such as WNV. The population endures long and sometimes brutal winter conditions for approximately five to six months of the year. A climate regime such as this dictates much of the population's activity. Recreation and outdoor activities are held at premium due to the limited time frame in which they can be enjoyed. Recreational green space is abundant in the state which does put the population at further risk of contracting WNV.

In addition the activity of vectors possibly carrying WNV coincides with the outdoor recreation months in Minnesota.

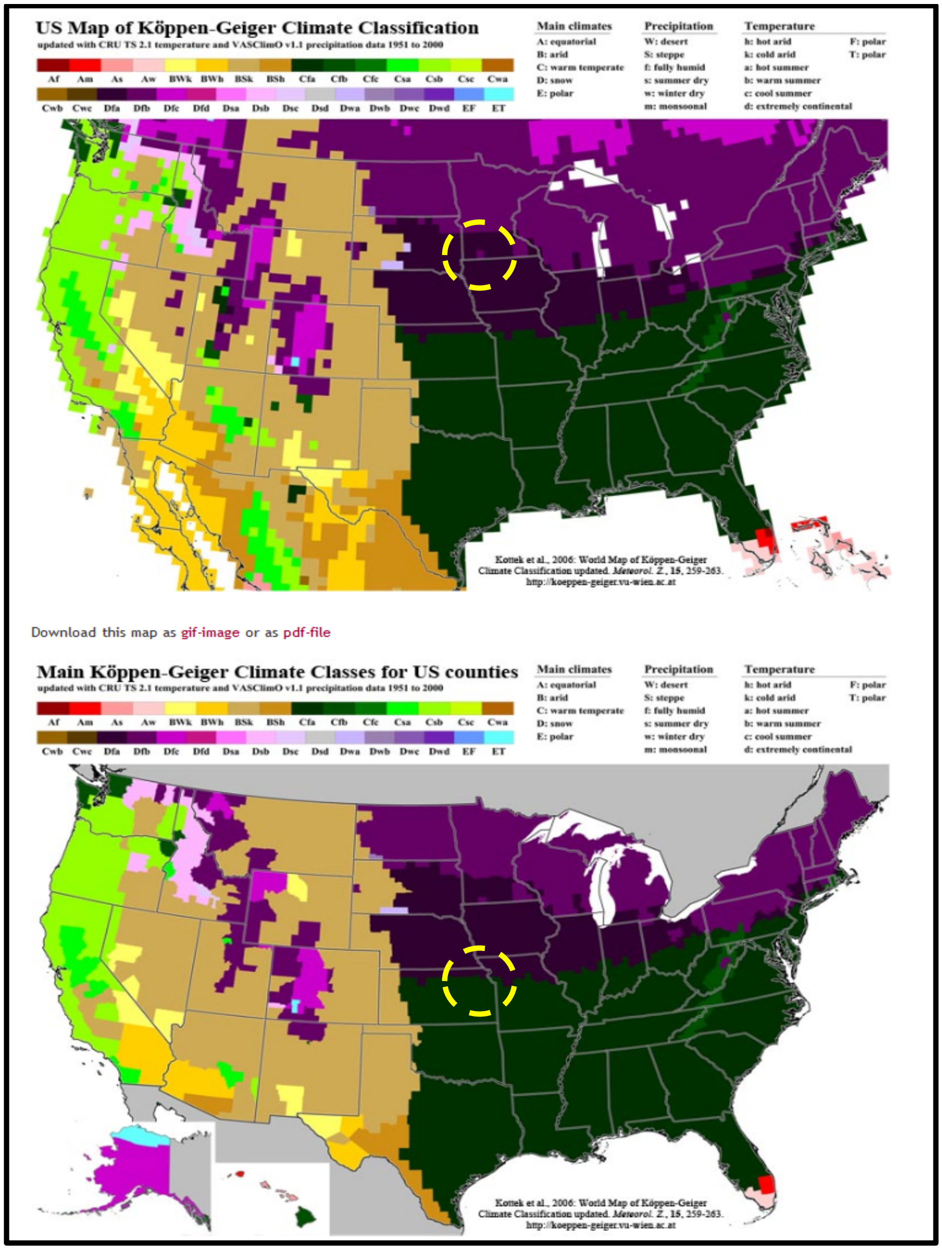


Figure 11: Köppen-Geiger Climate classification showing the location of Minnesota (yellow circle). The study area is effectively located in the two climate zones (Dfa and Dfb) making the climate cold, with hot/warm humid summers. (Brugger, 2012).

Temperature

Temperature is a factor that directly impacts the breeding cycle of the *Culex* mosquito (Sutherst, 2004). The mosquito breeding cycle in this area is bound by temperature in that it must range above 10^0C (50^0F) for the cycle to begin. Several days above this threshold will allow larvae to begin the process of escaping their winter cocoons. Climate change is slowly beginning to show its impact in the Minnesota River basin. A greater number of days ranging above the necessary threshold for breeding to begin are being recorded. These days are also beginning to appear sooner in the spring season allowing for the interaction between human and vector to be longer.

Precipitation

Precipitation plays its role in a different and more common way in the WNV cycle. The general public equates mosquito habitat with stagnant or "dirty" standing water and that certainly is a fact. This increase in ponding water can be due to environmental changes such as climate change. Additional factors involve the land surface where this increased precipitation is falling. Soil anomalies, impervious surfaces and artificial collection points all increase the amount of vector habitat. These changes can be variable and are imminently constrained by human impacts on the environment and the land surface.

IV Topographic landscape

Biomes

Minnesota is located in the Upper Midwest in the mid-continental United States. The state contains an area of 225,181km^2 and lies between 43.5 and 49 degrees north latitude approximately. This location defines the states vegetation and climate regime and also impacts the prevalence of environmental diseases such as WNV.

The US Forest Service and Minnesota DNR have developed an Ecological Land Classification Hierarchy (ELCH) system to define the myriad of ecotones that reside in Minnesota. These are broken down into three categories (provinces, sections, sub-sections) to better define the formation, vegetation and topography of each region. The state contains four provinces; eastern broadleaf forest, Laurentian mixed forest, prairie parkland and tall grass aspen. Figure 12 is a representation of the four defined provinces in Minnesota. Each of these biomes bears a different impact on a vector-borne disease such as WNV. The underlying vegetation structure, climate and drought level all play a role in whether a biome is susceptible to being a prevalent area for WNV to proliferate.

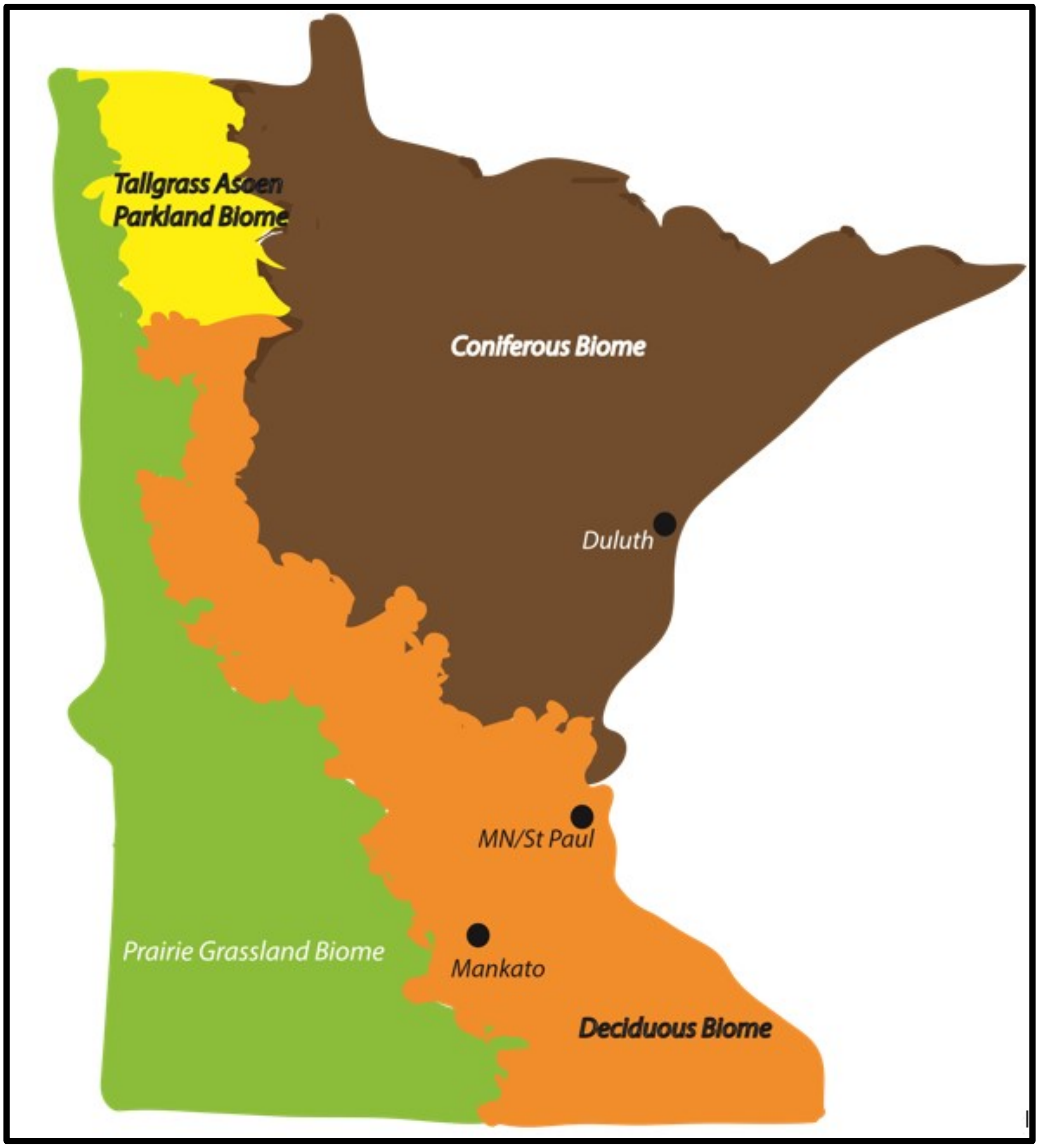


Figure 12: Ecological biomes in Minnesota. Map recreated from Minnesota Department of Natural Resources data using Adobe Illustrator CS6

Soils

The soils of Minnesota were affected by glacial activity and much of this activity deposited and is a direct reflection of the soil regimes in the state today. The Wisconsin Glaciation began approximately 75kya and was characterized by multiple pulses creating the landscape in contemporary Minnesota (MN DNR, 2014). The last three pulses impacted the topography of present day Minnesota immensely leaving moraines, eskers and depositional plains throughout the state largely consisting of glacial till. Figure 13 defines the pulses and the direction of flow from the Wisconsin glaciation and Laurentide ice sheet. The pulse action of the glacial advance can be seen in moraines and eskers that are distributed throughout the state and impacts population and farming patterns (MN DNR, 2014).

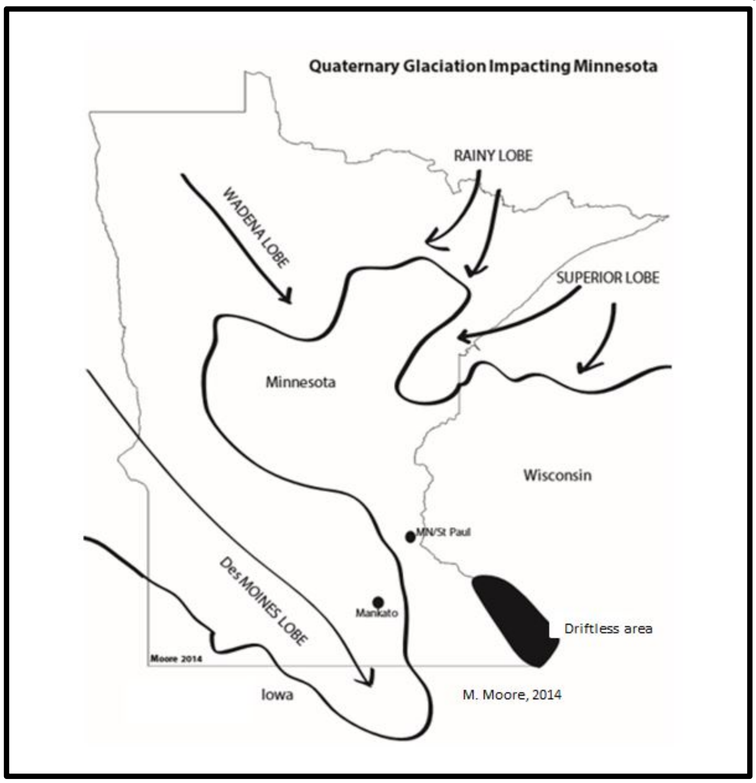


Figure 13: Idealized Quaternary glacial extent in Minnesota. Reproduced from data gained from the Minnesota Department of Natural Resources (MN DNR, 2014).

The last glacial extent deposited and formed the land on which Native and European peoples would eventually become settled. The soils that are located in the state allow for large agricultural operations to exist.

These soil regimes also allow for viable mosquito habitat to exist and in some place be abundant.

For the purposes of this study concern will lie on locations and types of surface soils and their placement throughout the study area. The state is dominated by 7 soil orders and they consist of Alfisols, Entisols, Histosols, Inceptisols, Mollisols, Spodosols, and Vertisols. The study area however is dominated by only two of these orders as well as two dominant sub-orders. Figure 14 depicts the dominant soil orders and the associated sub-orders in the United States.

Mollisols dominate the study area and have two dominant sub-orders in the area as well. Mollisols are characterized by having a dark color that is mineral rich and high in organic composition which is why it is prized as an agricultural soil in Minnesota. The development of mollisols typically took place under grasslands or areas that at one time was largely grasslands. Mollisols may have any of the defined temperature regimes but do not have permafrost. Mollisols can have any moisture regime, but enough available moisture to support perennial grasses seems to be essential (NRCS soil taxonomy, 1999).

The two sub-orders that are dominant in the area are Aquolls and Udolls. As their name hints aquolls are a mollic sub-order that develop in low lying areas and commonly collect water creating a ponding effect. Most of the soils have had a vegetation of grasses, sedges, and forbs, but a few also have had forest vegetation. In the United States, Aquolls are most extensive in glaciated areas of the Midwestern States where the drift or loess was calcareous.

Aquolls have aquic conditions or have been artificially drained. They can have any temperature regime from cryic to isohyperthermic (NRCS soil taxonomy, 1999).

Udolls are a mollic soil that is typically found in humid climates such as Minnesota. They formed mainly in late-Pleistocene or Holocene deposits or on surfaces of comparable ages. In the United States, their vegetation at the time of settlement was dominantly a tall grass prairie, but some of the soils on Pleistocene surfaces appear to have supported at some time a boreal forest that was supplanted by grasses several thousand years ago. Udolls formed in sediments and on surfaces of varying ages from Holocene to mid Pleistocene or earlier. The Udolls that have a thermic or warmer temperature regime, in particular, may have formed during two or more glacial and interglacial stages (NRCS soil taxonomy, 1999).

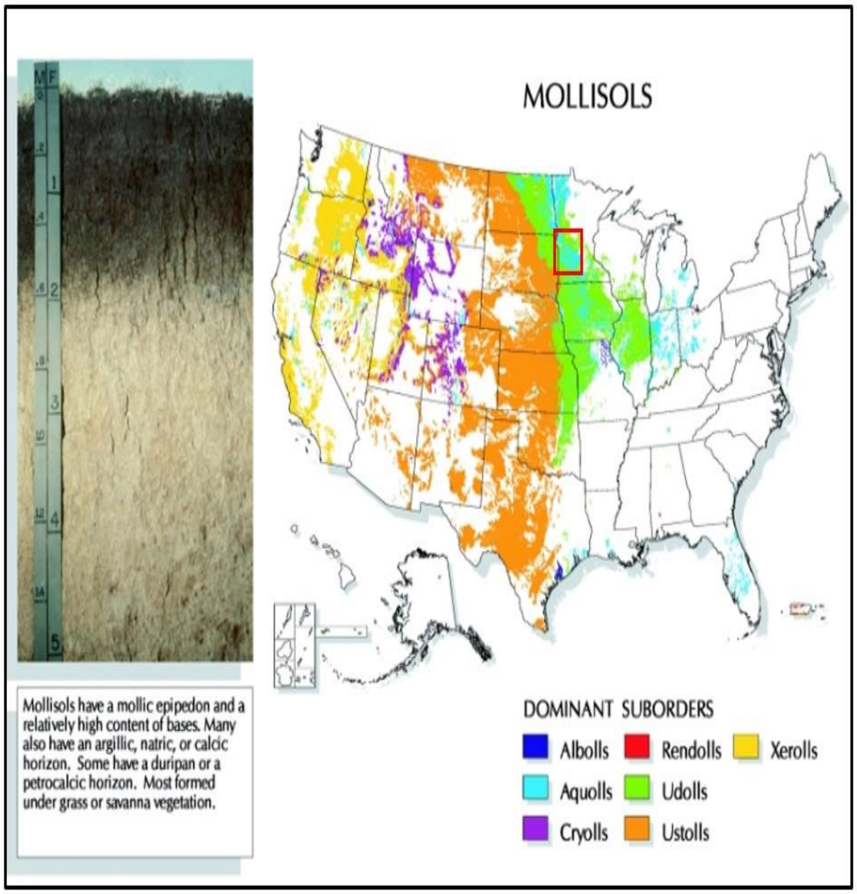


Figure 14: The National Resource Conservation Service (NRCS) provides soil data via SSURGO/STATSGO soil survey programs. The map above provided by NRCS depicts the dominant soil orders and sub-orders in the USA. The study area is outlined in red and illustrates that the study area is largely mollisols and its two sub-orders of aquolls and udolls (NRCS, 1999).

Lakes

As with the geology and soils in Minnesota the lakes, rivers and wetlands are a direct result of the last glacial maximum. Natural lakes can be found in all of Minnesota's eighty-seven counties except four (Mower, Olmsted, Pipestone and Rock) counties of which none lie in the study area (MN DNR/lakes, 2014). The amount of lake, river and wetland surface area is reported by the MN DNR to be 13,136,357 acres in the state of Minnesota. Mosquitos have a specific need for water in the breeding cycle and large amounts of water residing in Minnesota enable mosquito pools to successfully reproduce. The water bodies also attract human populations in their recreational activities and thus create more possible exposures between humans and vectors.

The study has counties that have much surface water and counties that have little surface water. The county with the most average surface water is Big Stone County and subsequently has recorded the most WNV cases to date in the study area.

Wetlands

Wetlands are a known repository for mosquitos and are somewhat of a requirement in the breeding cycle of the vector. However, other water bodies can be utilized in an area that lacks sufficient wetlands but wetland locations still play an important role in the abundance of vector breeding pools. In wetlands, the abundances of mosquito larvae are often limited by biotic factors, such as predators and competitors (Blaustein & Karban 1990; Blaustein & Margalit 1996; Blaustein 1998; Stav et al. 2000;

Mokany & Shine, 2003). In addition, the importance of these biotic interactions varies depending on the type of wetland (Chase and Knight, 2003). Three types of wetlands were identified in the study area; mixed, woody and herbaceous wetland ecosystems.

The land cover classifications used here are from the National Land Cover Definitions (NCLD) issued by the US Environmental Protection Agency (EPA), 1992. Woody wetlands are defined as "areas where forest or shrubland vegetation accounts for 25-100 percent of the cover and the soil or substrate is periodically saturated with or covered with water (NCLD, 1992)". These wetlands are important as their water levels fluctuate seasonally and show low levels at the end of the summer season. These types of wetlands are highly susceptible to the effects of drought.

Herbaceous wetlands are defined as, 'Areas where perennial herbaceous vegetation accounts for 75-100 percent of the cover and the soil or substrate is periodically saturated with or covered with water (NCLD, 1992)". These wetlands account for a large portion of the wetlands found in Minnesota and the study area.

Chapter Four

Geographic Analysis and Patterns of West Nile Virus: 2002-2012

I. Analysis of Population and Population Change

Populations fluctuate with time and most modern countries assess this by gathering data through a regular census cycle. The United States Census Bureau was formed in 1903 during the presidency of Theodore Roosevelt, (in the Department of Commerce). The Constitution of the United States (Article I, section II) directs that the population be enumerated at least once every ten years and the resulting counts used to set the number of members from each state in the House of Representatives and, by extension, in the Electoral College. The Census Bureau now conducts a full population count every 10 years in years ending with a 0 (zero) and uses the term "decennial" to describe the operation (US Census, 2012).

The Minnesota territory became a state in the union in 1858 and was largely settled by Scandinavian and German immigrants. Today, the state boasts a land area of 225,181km^2 and a population of 5,303,925 with a median age of 37.5 and 66.6 persons per square mile (US Census Bureau, 2010). WNV historically and most detrimentally impacts the young and the old of resident populations. These populations are at increased risk due to declining or not yet mature immune systems.

Analyses of changes in overall population per county, populations 5 years and younger as well as populations 62 and older were undertaken to assess whether population change has an impact on WNV prevalence in a rural setting.

The study area consists of 10 counties all of which border the Upper Minnesota River Valley in varying percentages. The last two census collections were used to asses change over a 10 year prescribed period. Overall, population was lost in all counties except Nicollet and Blue Earth counties. The largest loss of population occurred in Swift County with a decrease of 18.2% in overall population. Blue Earth County recorded the largest population increase at 14.4% over the sample period (10 years). Blue Earth County contains the largest city center and largest retail and commercial focus in the study area and therefore the increase does not seem anomalous as historically rural populations migrate to more urban centers to obtain more employment opportunities and financial stability. Refer to figure 10 for population distribution within study area.

However, in populations at highest risk of contracting vector borne disease some concerns were seen. In populations aged 62 and greater declines were seen in all but two counties. Brown County saw an increase of 300% in persons aged 62 and older; while Redwood County saw an increase of only 0.54%. Populations 5 and younger proved to have a mixed result with 5 counties seeing increases and 5 counties observing decreases in this population set. The largest increase was seen in Nicollet County at 20.7% and largest decrease was in Brown County at 70.6%. The percent change in population was calculated using a universally accepted equation, ***((y2-y1)/y1*100*** (US Census/pdf).

Discussion

The analyses of populations within the study area were significant in that they showed a difference does exist in the patterns of WNV in rural areas as opposed to areas of heavy urban development. In a previous study, Debarchana Ghosh 2009, within the Twin Cities metro area (historically the highest reporting seven counties in the state) it was shown that urban areas offer significant *Culex* vector breeding sites with artificial containers such as ponds, buckets, and bird baths being common (CDC, 2013). The increased infrastructure in the urban location also provides widespread breeding locations with storm drains being the preferred site.

Rural locations pose a whole different set of factors that need to be considered in the prevalence of environmental diseases such as WNV. Big Stone County is the highest reporting county for WNV in the study area. This county also contains within it one of the lowest populations in the study area. The factors that differ from an urban location to a rural location such as Big Stone include increases agriculture, increases ponding water sites, more natural wetland locations, more outdoor employment, proximity to a very high reporting state (South Dakota) also may play its part. In contrast Nicollet County has one of the highest total populations in the study region and has reported only one case over the 10 year period. Although Nicollet contains more people it contains relatively less prime vector breeding locations.

III. Analysis of Human WNV Cases

WNV and its proliferation in the United States has been exponential as its geographic prevalence as it moved from New York in 1999 to the western coast of the US in 2004 which included large clustering outbreaks in many locations of the country. Refer back to figure 6 for proliferation across the United States. WNV first appeared in Minnesota in 2002 with 48 confirmed cases spread throughout the state. Four of those cases appeared in the study area and within four different counties; Lac qui Parle, Swift, Chippewa and Redwood Counties. Figure 15 illustrates the initial presence of WNV by year, county and the number of cases reported when it first appeared. In 2003 Minnesota saw an outbreak year with 148 cases confirmed impacting 56 counties and producing 4 deaths. This outbreak year (2003) saw Renville and Blue Earth Counties being the highest reporting in the study area with 5 cases each. Within the study area all counties reported cases with the exception of Nicollet County. Minnesota has also experienced outbreak years in 2007 (101 cases), 2012 (70 cases) and in the year 2013 (79 cases).

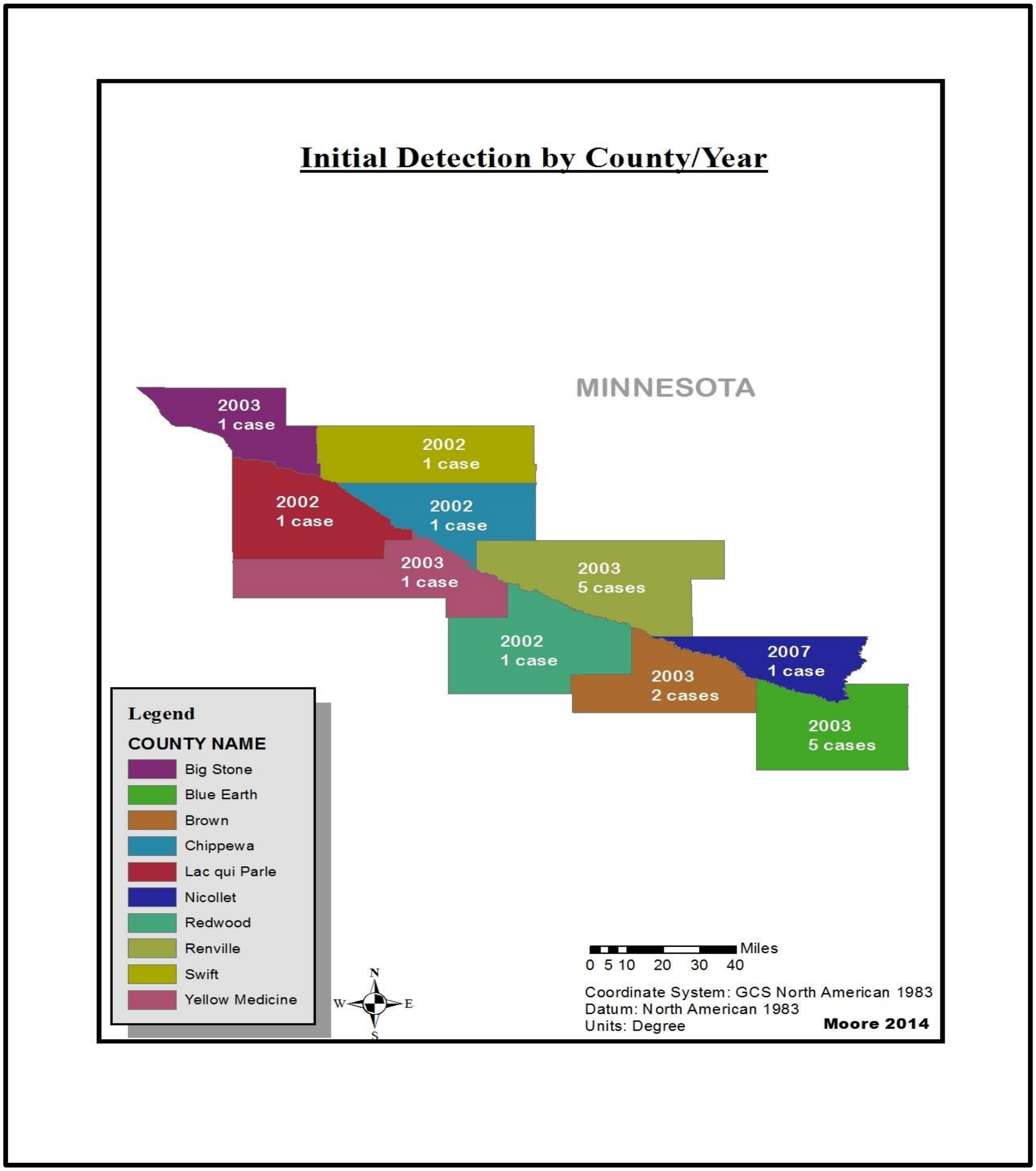


Figure 15: GIS derived map clipped to the study area. The map indicates the initial detection of WNV by CDC confirmed case data (CDC, 2003). 4 counties reported cases in 2002, the first year WNV was detected in Minnesota. 2003 was an outbreak year in Minnesota with higher number reported in Blue Earth and Renville counties. Nicollet County did not have a confirmed human case until 2007.

A t-test was performed in order to obtain a probability of acquiring WNV, displayed in table 5. The CDC provides an open source application to compute disease statistics called Epi Info 7 and can be found at http://wwwn.cdc.gov/epiinfo/. The county with the highest number of cases over the study period, Big Stone, was compared with the county reporting the fewest cases, Nicollet.

Input Data				Two-sample Independent T-Test				
Group	Sample size	Mean	Std. Dev.	% confidence			Group 1	Big Stone County
1	12	1.090909	2.34327	95			Group 2	Nicollet County
2	1	0.090909	0.30151	95				
Result								
	t statistics	df	p-value	Mean difference	Lower limit	Upper limit		
Equal variance	0.410012	11	0.6897	1	-4.36813	6.36813		
Unequal variance	1.35026	0	<0.0000001	1	0.99999	1		

Table 5: Two-sample independent t-test with a 95% confidence level. The two samples used were the county of highest reported incidence, Big Stone, and the county with the lowest reported, Nicollet. The equal variant p-value indicates a high probability of contracting the virus, 69%. See text for further explanation.

Although the probability indicates a significant possibility of contracting the virus it is still quite variable in nature. The variability is heavily dependent on the physical factors from the environment which is dynamic and ever-changing year by year. This t-test is indicative of acquiring the disease in a perfect uniform world with all variables in all counties being equal. However, each county presents with its own unique microenvironment and population characteristics and therefore this result is simply one of many factors needed to ascertain an overall probability of disease contraction by an individual. As with all environmental diseases at times conditions align themselves in a way that allows for outbreaks or epidemics to occur. Minnesota has seen several outbreak years and an increase in reported cases in the study area were noted. Figure 16 illustrates data from the 2003 outbreak in Minnesota.

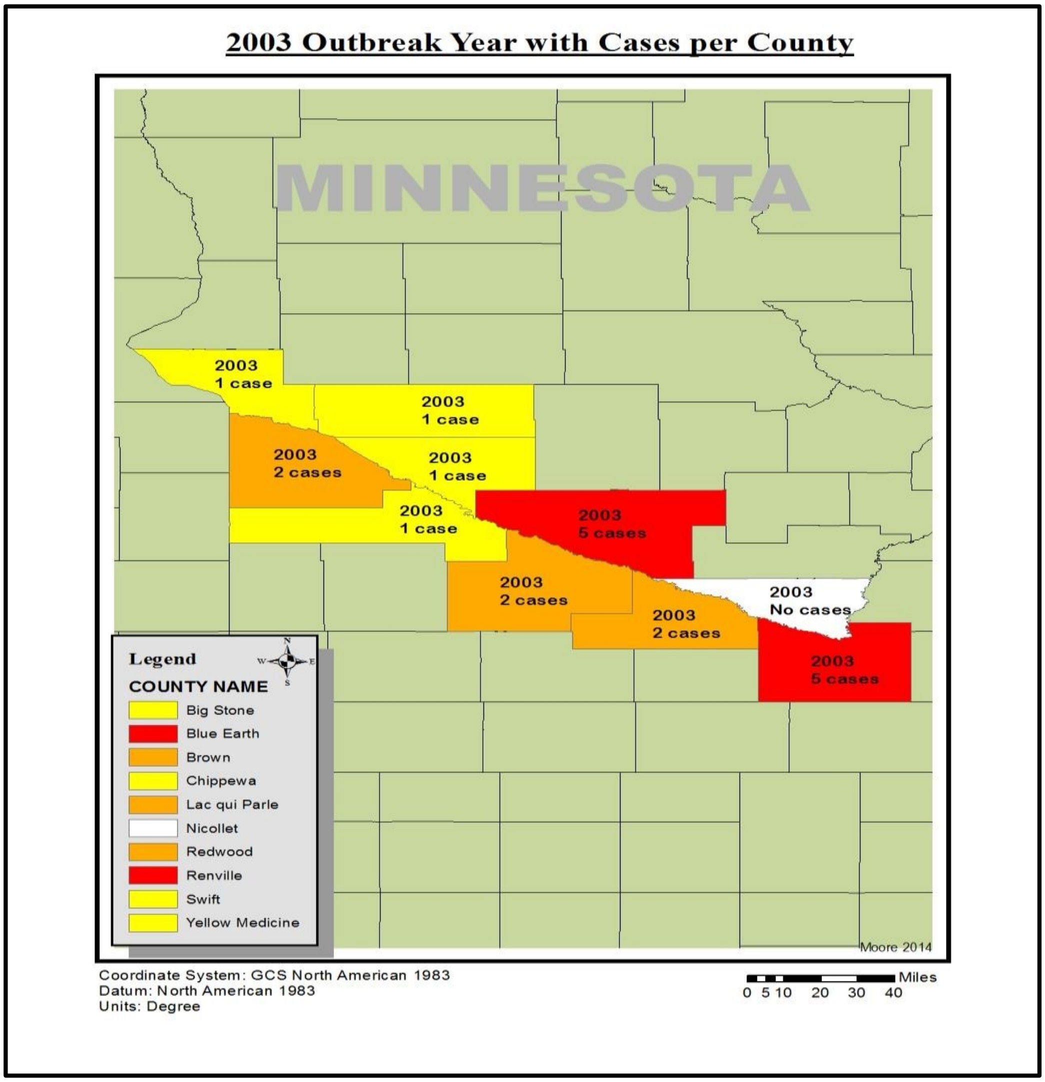


Figure 16: Outbreak years of an environmental disease present a unique time when more individuals are at risk. In 2003 Minnesota reported 148 cases in 56 counties. In the study area a total of 20 cases were recorded. All counties were above the study period average with the exception of Big Stone County which was equal to its average.

Discussion

The pattern of WNV in the Upper Minnesota River Valley is complex. Examined yearly the pattern is random but overall there does seem to a clustering of numbers over time. Figure 17 illustrates the pattern by county for total amount of cases reported over the study period, 2002-2012. Data limitations from HIPAA severely constrain the analysis that can be undertaken for this attribute. This attribute was considered in a more general context and the initial null hypothesis, Ho_1 – The spatial distribution of WNV is random in the Upper Minnesota River Valley, and therefore the null hypothesis cannot be rejected.

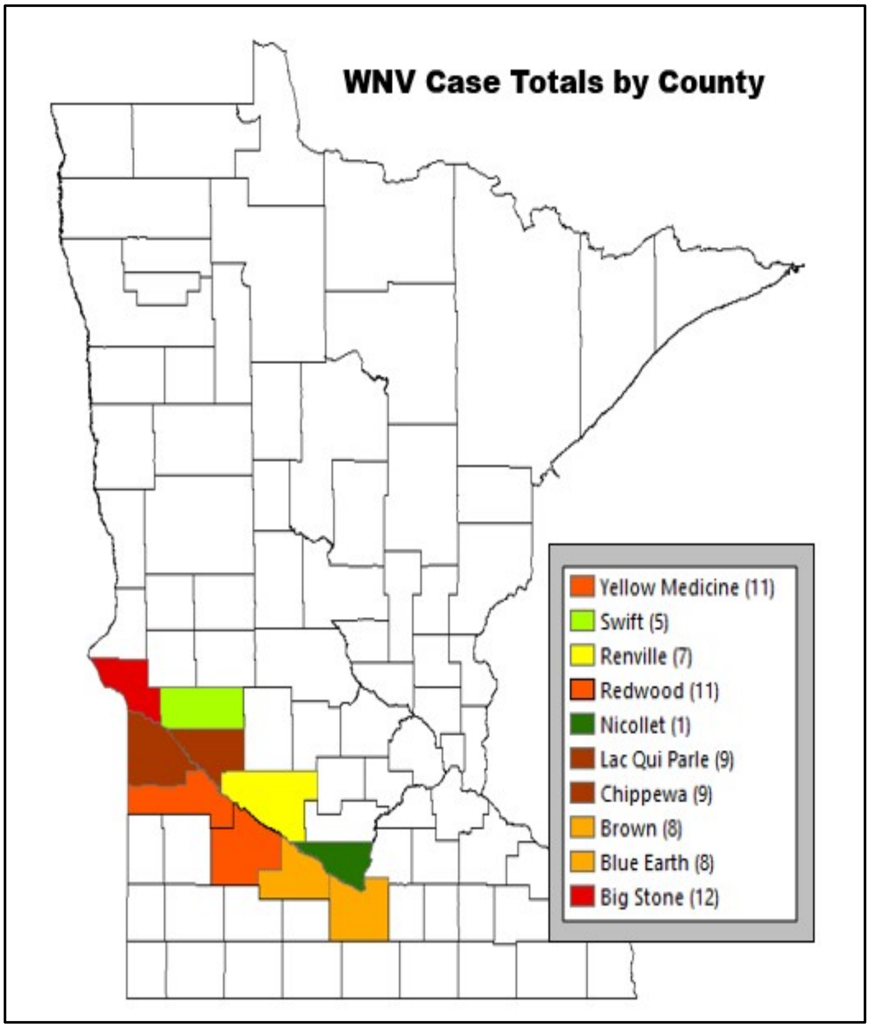


Figure 17: WNV cases by county over the study period 2002-2010.

IV. Analysis of Climate Factors

Climate directly influences the biology of disease vectors and thereby their abundance and distribution. The relationship between climate and mosquito density is a result of greater availability of breeding sites for mosquitos that comes with higher rainfall, and higher temperatures, which increase developmental speed (Sutherst, 2004). The climate is by nature variable and this is what distinguishes it from weather but as the climate evolves so does the weather patterns and vector breeding habits. Intensity in rainfall and temperatures can vary wildly creating larger storm patterns, increasing longevity of storms and thereby increasing pooled water on the ground and in turn increasing mosquito abundance.

In 400 B.C. Hippocrates in his book “On Airs, Waters, and Places” reported the importance of the climatic conditions and their impact in the occurrence of various diseases and epidemics. This fact fits perfect for arboviral diseases, including WNV infections (Papa, 2013). Apart the role of the weather patterns on the abundance of mosquitoes and birds; they may affect the bird migration in time and space. It has been shown that short-term variation in environmental conditions (weather and habitat) might promote route flexibility (Vardanis et al., 2011).

Mosquito abundance and subsequently the prevalence of WNV is highly dependent on temperature and precipitation. *Culex pipiens* mosquitos are extremely sensitive to temperature and typically vulnerable to large precipitation events in the urban setting.

Previous studies have already confirmed that mosquito population densities vary strongly with temperature (Chuang et al., 2012). This is due to the temperature dependence of the development rates of eggs, larvae and pupae, survival rates of immatures. Temperature also influences the length of the gonotrophic cycle (Madder, Surgeoner, Helson, 1983). The gonotrophic stage is defined as the condition of female mosquitoes during blood ingestion, ovarian development, leading to lying of larvae (tromped.org).

The climate was analyzed by specific factors including a temperature threshold of 50^{o}F and for rainfall amounts. Data were obtained from the Minnesota Climatology Working Group and included an average of 7 observation stations in Big Stone County and 20 in Nicollet County (MCWG, 2014). The difference in observation stations is a reflection of resident population sizes; Nicollet County has a significantly larger population. Table 6 details a comparison of the number of days above 50^{o}F spread over the study period, 2002-2012.

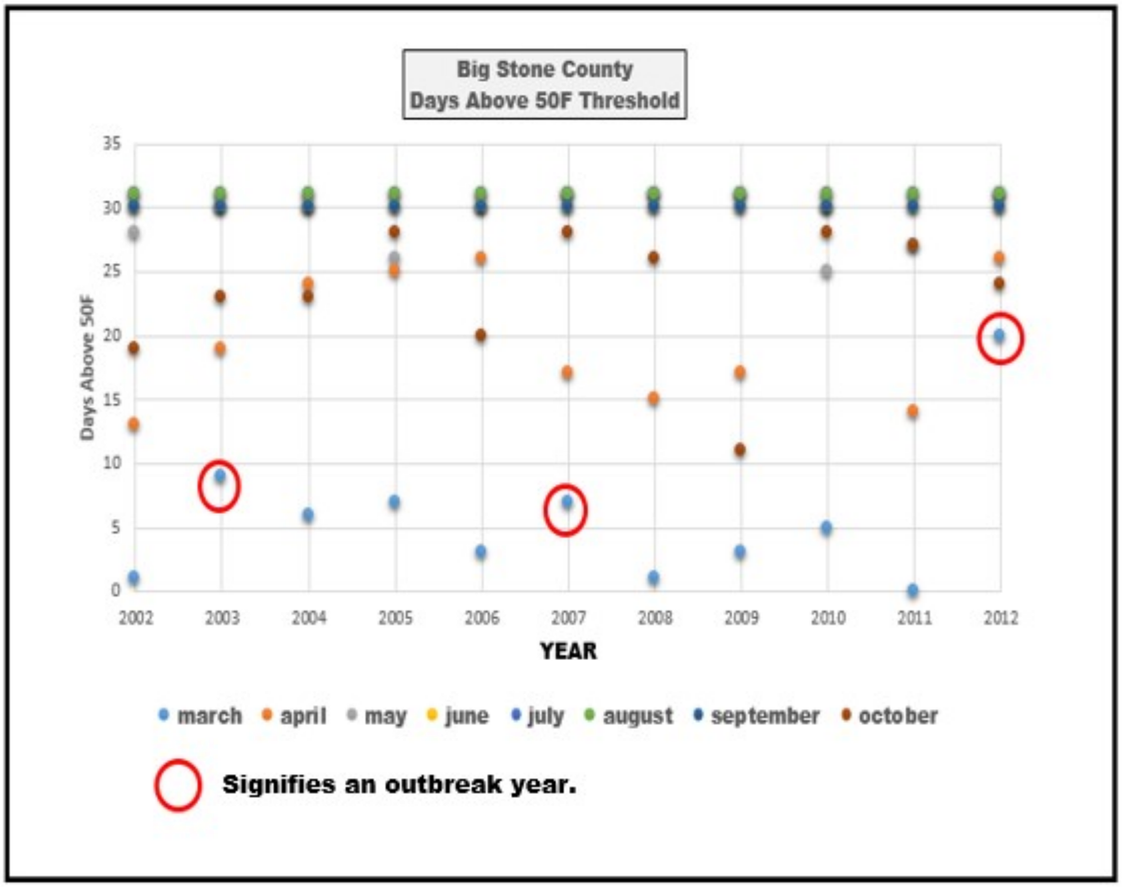


Table 6: Comparison of years during study period and days above 50^{0}F. It is noteworthy to point out that in outbreak years (red circle) more days above the 50^{o}F threshold needed to initiate larval emergence was seen earlier (MCWG, 2014).

The Center for Disease Control and Prevention is only one of the many agencies that track disease in the US. The United States Geological Survey's (USGS) division of National Wildlife Health Center tracks WNV in the US by state as well. They produce yearly maps and graphs depicting total amounts and initial day of the first reported case in that year. Figure 18 is a set of graphs from the USGS National Wildlife Health Center's data webpage for WNV tracking. In figure (A) random graphs were chosen from years

within the study period that had a lower number of days above 50^0F in the county with the highest reported cases. Figure (B) is the same graph mosaic with data from outbreak years within the study area. It is clear that years with lower or colder climate conditions where less days of 50^oF are seen in March ultimately delays the onset of reported cases and additionally suppresses the amount of cases seen per season. In figure
(B) the outbreak years, it is significant that these years had a high number of days above 50^0F which initiated an earlier WNV season and a more abundant amount of cases overall.

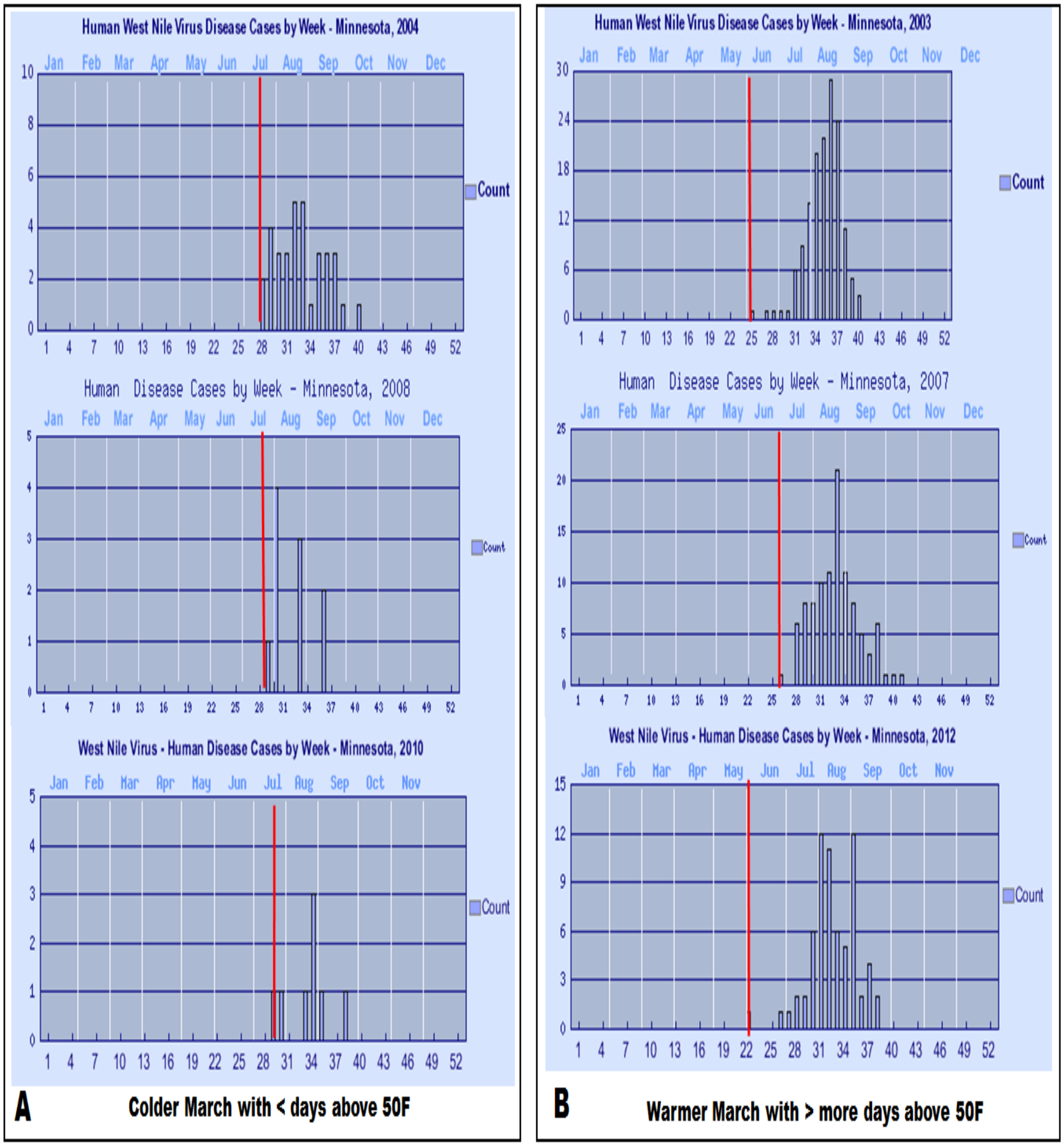
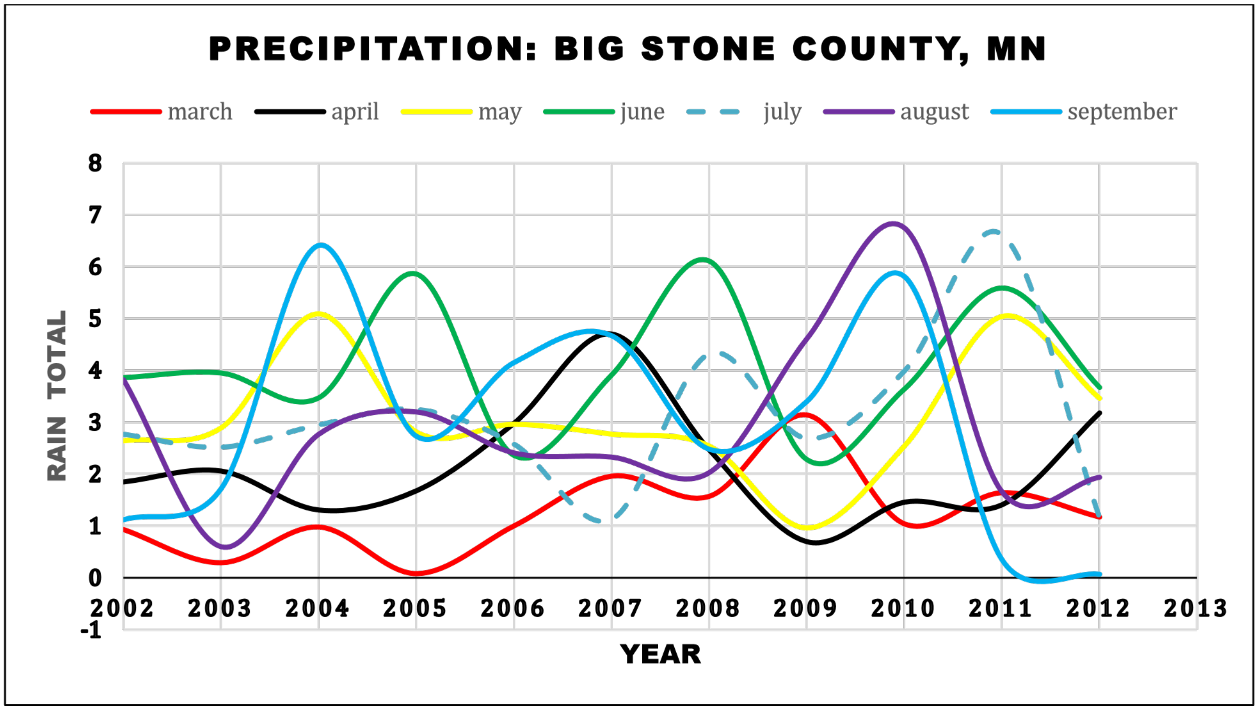


Figure 18: Comparison of USGS data illustrating the impact climate has on vector abundance and subsequent WNV prevalence. (A) Indicates low WNV case years where there were few or zero days above 50^{o}F in March resulting in a delayed onset of cases reported and decreased abundance. (B) Indicates break out years with a warmer climate, high incidents of WNV an earlier onset of diagnosed cases was seen. Data was obtained from USGS National Wildlife Health Center webpage (USGS, 2014).

Precipitation also plays a distinctive role, similar to that of temperature. Precipitation in the two sample counties is quite uniform in nature. In some years Big Stone County does exhibit higher precipitation totals but from a climate perspective the counties contain similar amounts of measurable precipitation over time.

Precipitation is a proverbial double-edged sword for mosquitos as it can create puddles or ponding water locations that allow for breeding to occur, and the opposite can be said for locations such as storm drains that ultimately flush larvae rafts out during precipitation events and therefore decreasing vector abundance. Nicollet County does have a larger population and larger urban centers and the possibility exists that any vectors taking refuge in storm drains are likely being wiped out during months of high precipitation and in turn decreasing vector and WNV abundance. Table 7 illustrates precipitation per year/month over the study period. It can be noted here that years such as 2010 with high precipitation in both counties are also years of low WNV prevalence. Table 8 illustrates the average precipitation for the two counties over the study period. June is the wettest time during the mosquito season for both counties and the trends in both counties are very similar. The R^2 result for the logarithmic trend however is very low and confidence in an increasing trend is not felt to be viable.



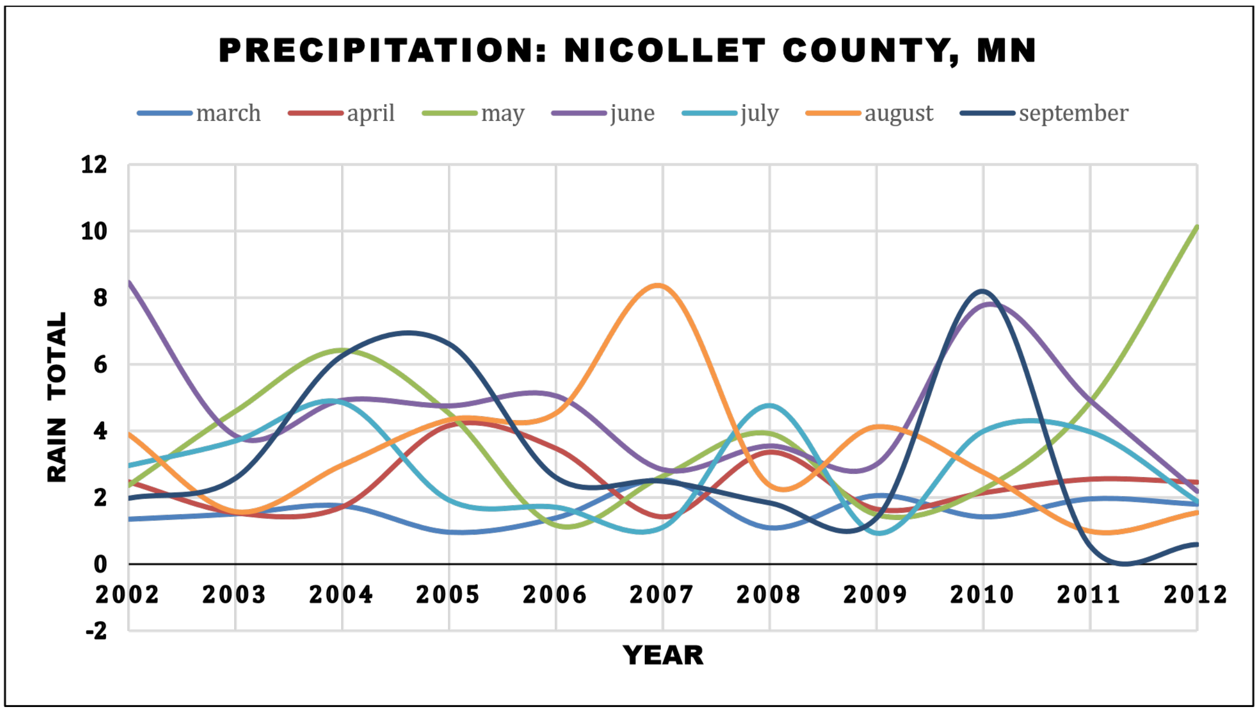


Table 7: Precipitation over the study period for the highest and lowest reporting WNV counties. Data sourced from the Minnesota Climatology Working Group.

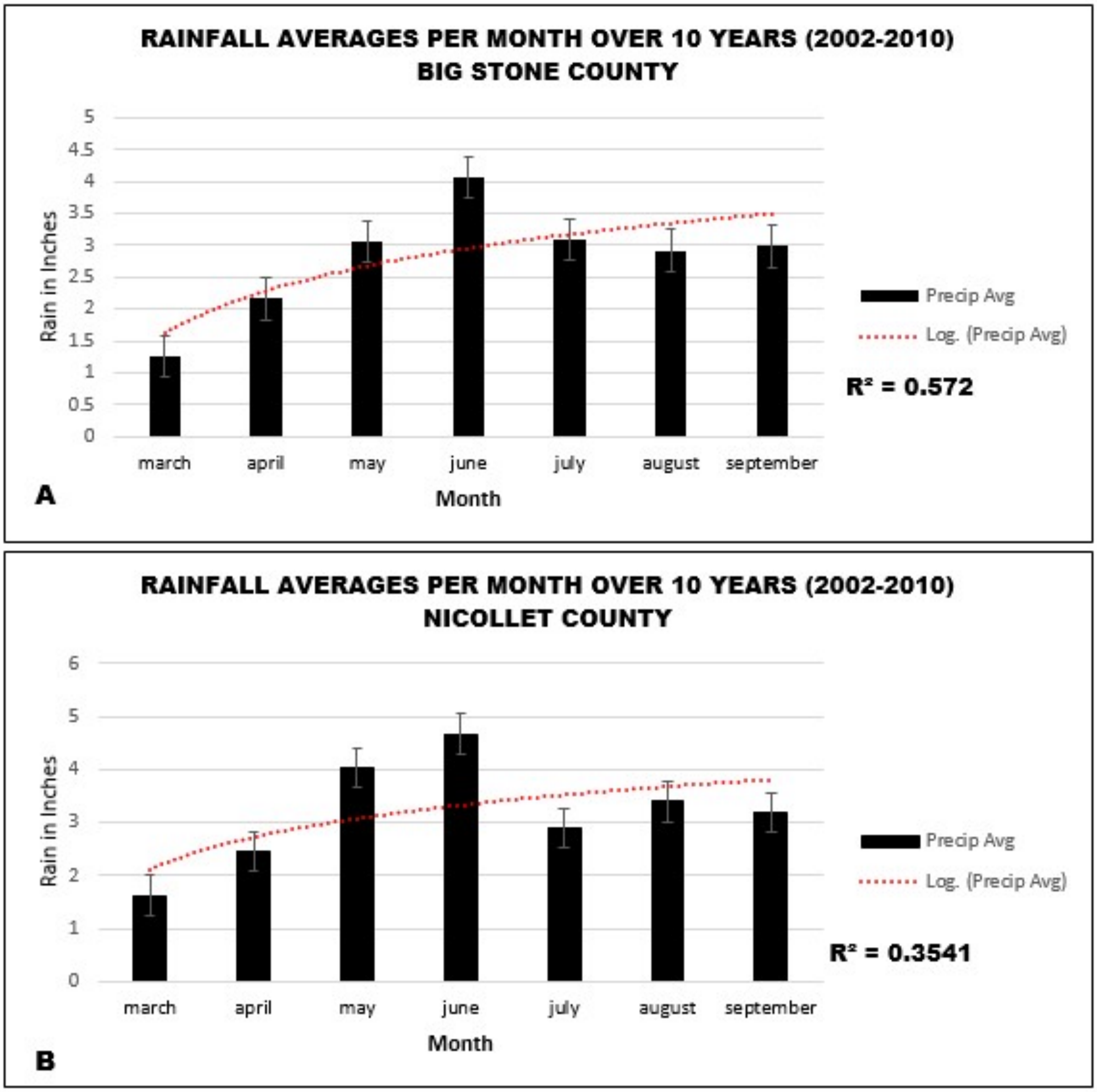


Table 8: Precipitation averages for Big Stone and Nicollet Counties over the study period by month. *Culex* mosquitos are highly vulnerable to high precipitation levels. They are vulnerable to having larvae rafts washed away by large precipitation events and therefore interrupting the breeding cycle.

Discussion

The complexity of some causal pathways makes attribution difficult. Recent climate change might have contributed (via changes in temperature, rainfall, soil moisture, and pest and disease activity) to altered food yields in some regions (Zell, 2004). The data for the two county comparison shows that temperature does have the most influence over vector abundance. The data suggests that when more days over 50^0F are recorded in March the possibility of a more active vector season will be seen. This also suggests than an increase possibility of contracting WNV in these years is probable. This temperature allows for early larvae to be dispersed extending not only the season but abundance of mosquito pools and therefore transmission of the virus. In respect to the hypotheses for these attributes, Ho_4 – An increased number of days above 50^0 F in March does not increase the occurrence of WNV, is rejected as temperature most certainly impacts the prevalence of WNV. The alternate hypothesis, Ha_4 – An increased number of days above 50^0 F in March does increase the occurrence of WNV, is a proven statement by the data.

V. Analysis of Land Surface

Land cover regimes and their various topographical features provide habitat for all forms of life from insects to humans. Humans are an exceedingly adaptable species that have the ability to live in nearly all climates, at nearly all elevations and in nearly all biomes. Mosquitos have proven to be extremely adaptable as well but are constrained by some geographic features depending on mosquito type.

Human land use changes have been linked to mosquito community composition and concurrent changes in disease transmission patterns (Patz et al., 2000 Norris, 2004; DeGroote et al 2008). For example, human WNV incidence was strongly associated with rural agriculture row crop settings in Iowa (DeGroote et al., 2008). The analysis in this section will compare and contrast elevation, forest and grass/shrub land cover regimes in the study area.

Elevation

Elevation has been shown to constrain disease and its geographic prevalence in human populations (Randolph and Rogers, 2010). Arthropod or vector-borne diseases are especially sensitive to elevation differences. These vectors are restricted by the different ecosystems, climates and microclimates that are dominant at different elevations. Minnesota is located in the northern Great Plains in the United States and therefore the typical topography is rolling hills, open grasslands, wetlands and intermittent forest belts. This leaves the area with little elevation change from one county to the next. This uniformity suggests that elevation should have no overriding impact on the prevalence of WNV in each county.

However, a comparison was done between the highest reporting counties and the lowest reporting counties to explore any elevation anomalies that may present themselves. Nicollet County had the lowest reported WNV cases during the study period with only one. The highest reporting county was Big Stone County with 12 cases.

Figures 18a and 18b illustrate the difference between the two counties, which is minimal.

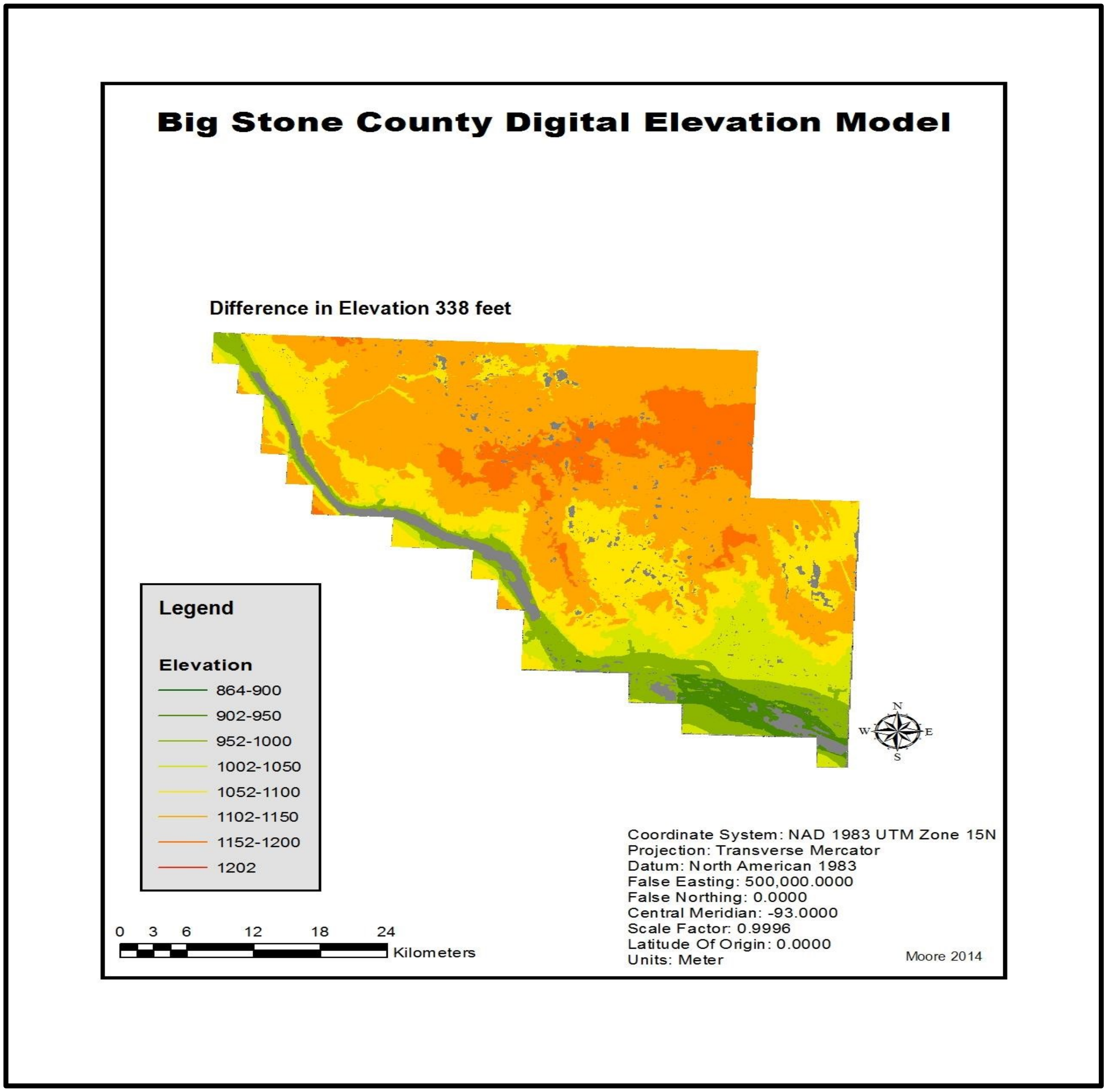


Figure 19a: GIS digital elevation models rendered using 3 meter LiDAR data from the Minnesota Geospatial Information Office (MN GEO). The data was manipulated in ESRI® ArcMap 10.1 where elevation contours were grouped and color coded. Big Stone County has a high point of 1,202 feet above sea level and an elevation difference of 338 feet. Although the elevation difference between counties is a mere 22 feet Big Stone exhibits more low lying terrain in its southeast corridor. This area also coincides with large wetland areas not found in Nicollet County and are ideal locations for vector breeding pools to proliferate and subsequently spread though out the county.

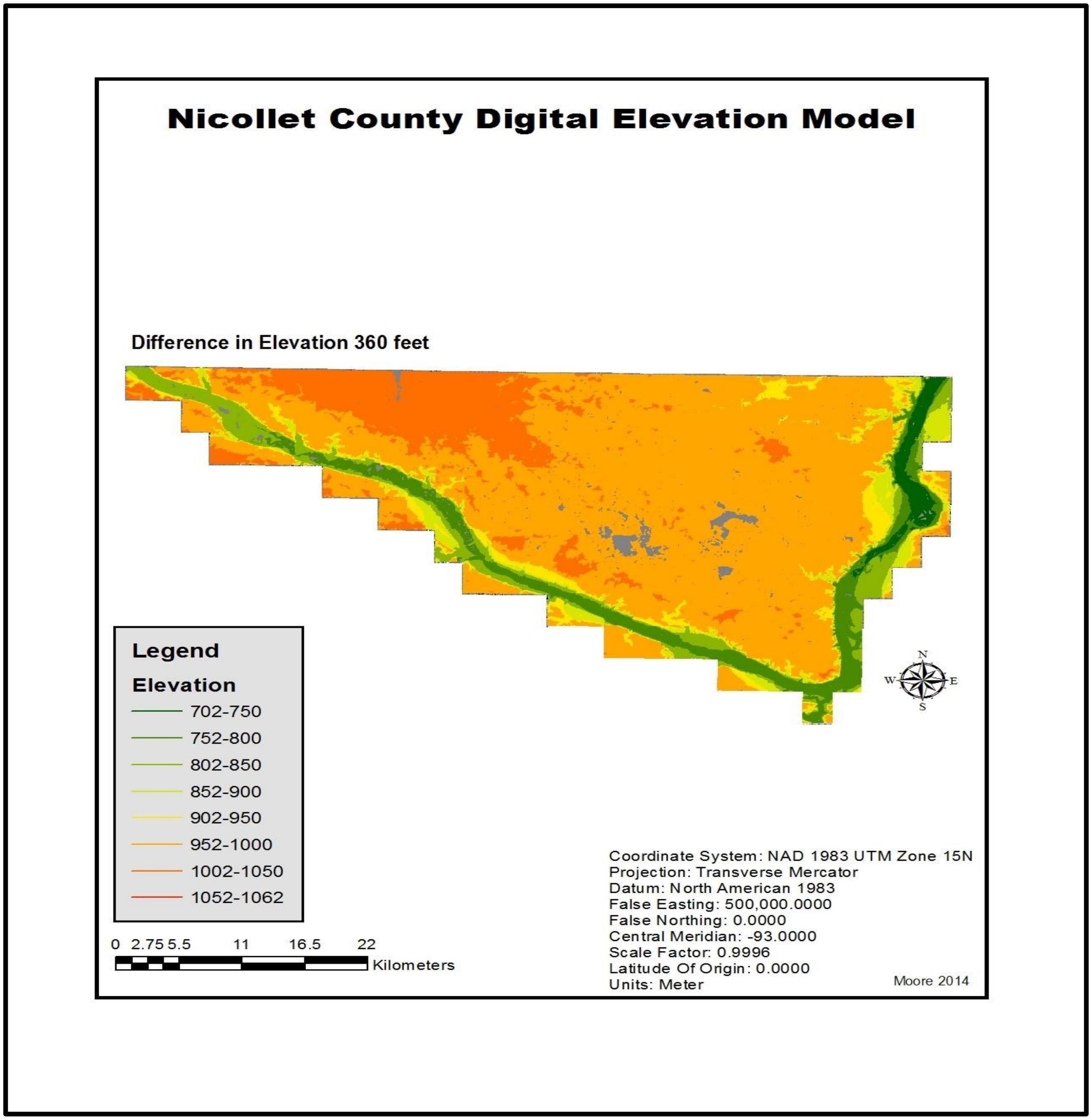


Figure 19b: GIS digital elevation models rendered using 3 meter LiDAR data from the Minnesota Geospatial Information Office (MN GEO). The data was manipulated in ESRI® ArcMap 10.1 where elevation contours were grouped and color coded. The highest point in Nicollet County is 1,062 feet above sea level with an elevation change of 360 feet.

Discussion

Sequelae of global warming are the world wide retreat of montane glaciers (Thompson et al.,1993; Kaser, 1999) and the observed rise of the 0 °C isotherm in tropical mountains by about 150m since 1970 (Diaz and Graham, 1996). Also, it has been observed that plants migrate to higher altitudes (Grabherr, Gottfried and Pauli, 1994; Pauli et al., 1996). Likewise, it is assumed that temperature-sensitive insects spread their habitats into highland regions (Zell, 2004). Overall elevation change between a high and active reporting county and a lower reporting county is minimal at 22 feet. Although elevation plays a role in extending the reach of disease as ecosystems migrate up a mountain ecosystem in a changing climate that is not the case in the study area. The relatively equal elevation throughout the study area suggests that this particular attribute is not an overwhelming factor in the prevalence of vector habitat and therefore WNV. However, this is subject to scale variations. At the county scale the impact is likely lower than would be seen at a local or micro-scale variation.

VI. Forest Cover

Big Stone County

Forest cover presents its own unique set of characteristics in respect to environmental diseases. Southern Minnesota and the study area specifically have sparsely placed and mostly human designed forest covers. The area exhibits many of the traits found in an agrarian society as agriculture dominates the economy and the landscape in the area.

County forest cover was mapped using two orthorectified aerial photographs from the years 2007 and 2010. Orthorectification is an important process in using aerial imagery. Orthorectification is the process of correcting the geometry of an image so that it appears as though each pixel were acquired from directly overhead. Orthorectification uses elevation data to correct terrain distortion in aerial or satellite imagery (ESRI online support, 2014). Forest cover data sets were obtained from the US Department of Agricultures (USDA) National Agriculture Statistic Service and used as training data in Erdas Imagine. Aerial imagery was used to create supervised classification data sets of forest cover within the two counties.

The two data sets were fused and manipulated in ESRI ArcMap 10.1 and analyzed for any forest changes. The forest locations were noted and remain possible repositories of vector breeding habitats. All forest cover in the study areas are subject to intermittent periods of flooding from precipitation due to the rolling, hilly topography of the land. The forest cover is broken up into three possible categories; woodland forest, evergreen forest and mixed forest.

Big Stone County was mapped as it exhibits the highest reported number of WNV cases overall. Nicollet County was mapped as the county with the lowest reported cases. Figure 19a is a digital comparison of forest cover change from 2007 to 2010 in Big Stone County. An increase in forest cover was noted with 25.05 hectares gained by 2010. Big Stone County as noted earlier is heavily cultivated. Figure 19b exhibits the same county mosaic at 1:80,000 scale increasing resolution of land cover features.

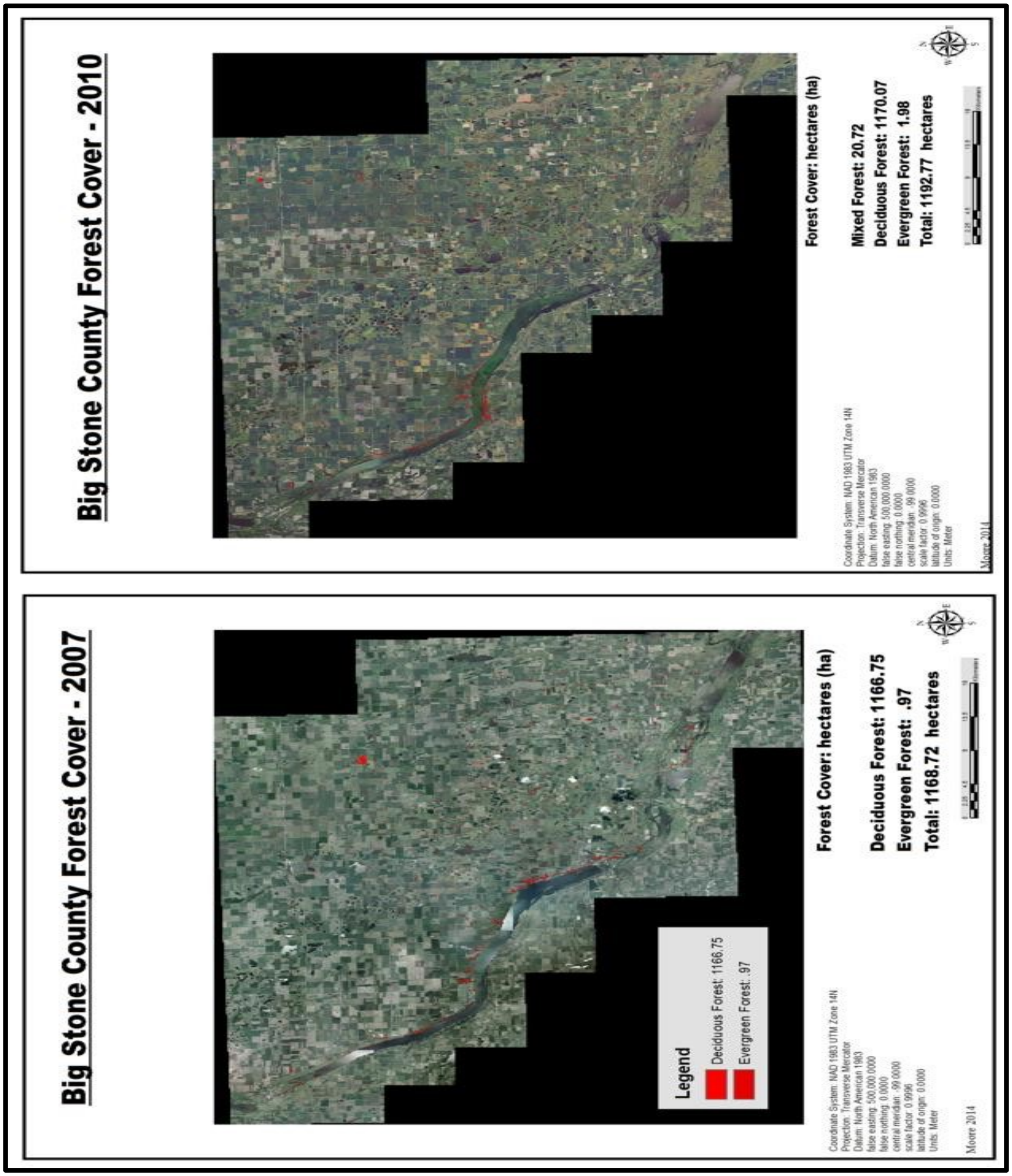


Figure 20a: A change was noted in forest cover however with an increase of 25.05 hectares. The change exerts minimal influence in available habitat for vector breeding.

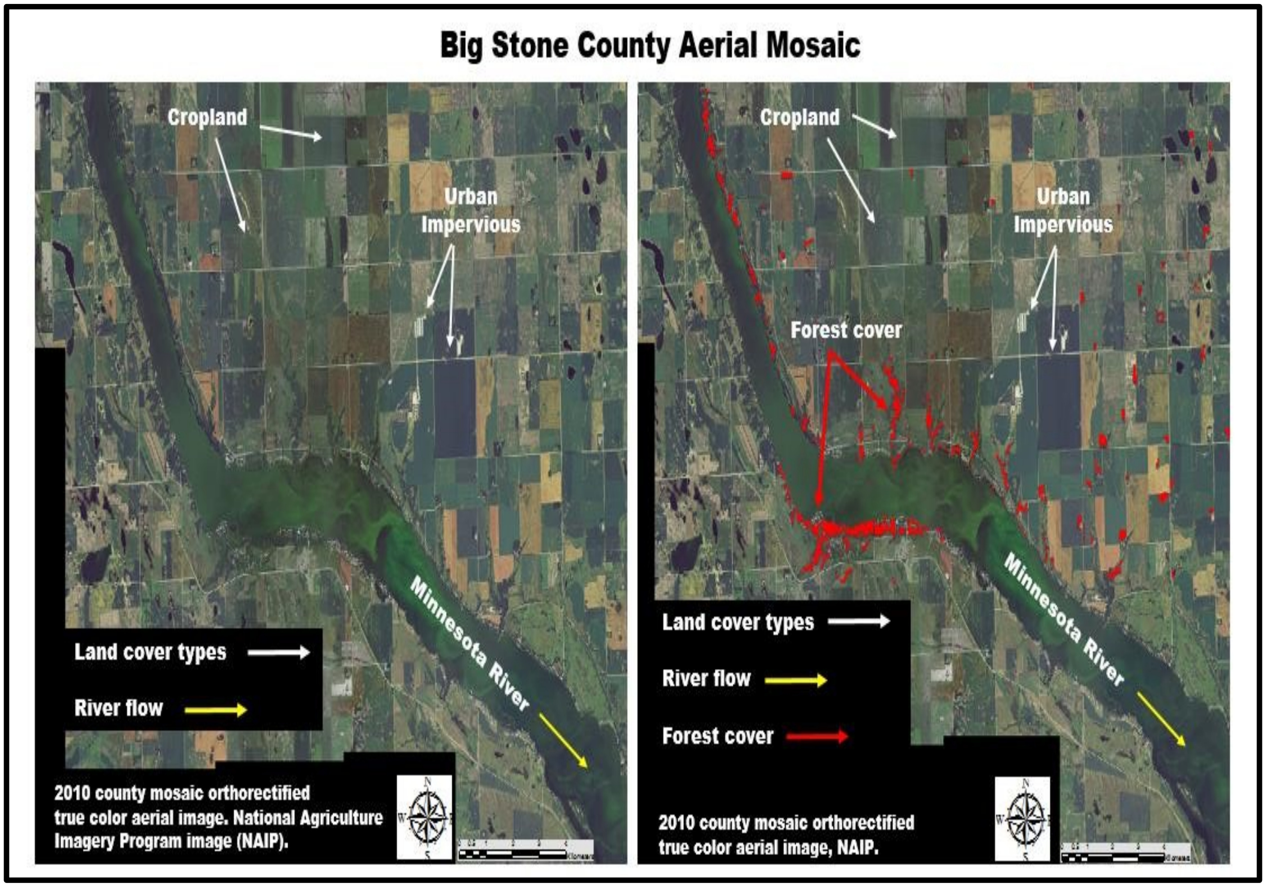


Figure 20b: At this scale (1:80,000) forest cover can be seen as heavily fragmented and largely located within the river basin. Cultivation dominates the landscape with small urban/residential impervious surface sparsely placed throughout.

Nicollet County

Nicollet County has an area of 1210 $km^2$and exhibits many of the same topographic features as Big Stone County but in significantly different proportions. The county is largely cultivated as well and this will be addressed in section 4.5. However, this county exhibits much larger tracts of forest cover, larger urban centers and less surface water locations. The county routinely has within it over 6,000 hectares of forest cover and much of this cover is continuous and non-fragmented. Like Big Stone County much of this forest cover is also contained within the river corridor. A difference was noted in forest cover over the four year span; an increase of 126.88 hectares was seen.
Figure 20a is an orthorectified county mosaic set from NAIP for years 2007 and 2010. The same fusion and analysis process used for Big Stone County was used here to maintain continuity. Figure 20b is scaled to 1:80,000 to show county characteristics.

After analyzing the two counties for forest cover Nicollet County contains significantly more hectares of combined forest types (deciduous, evergreen and mixed), 5440.68. Both counties gained forest cover over the sample period of 4 years. However, the cases of WNV did not change as Big Stone continued to report cases and Nicollet has reported only one case over the 10 year total study period. This leads to the result that even though Nicollet contains more forest cover that this habitat is not increasing vector abundance and therefore WNV cases. It is also possible that the location of the forest cover in both counties being largely isolated to the river corridor that humans frequent these areas far less than cultivated, urban or wetland locations.

In conclusion, the data suggests that forest cover is not playing a major role in the prevalence of WNV in the study area. This conclusion is limited by the data available and further discussion of limitations will be addressed in chapter 5.

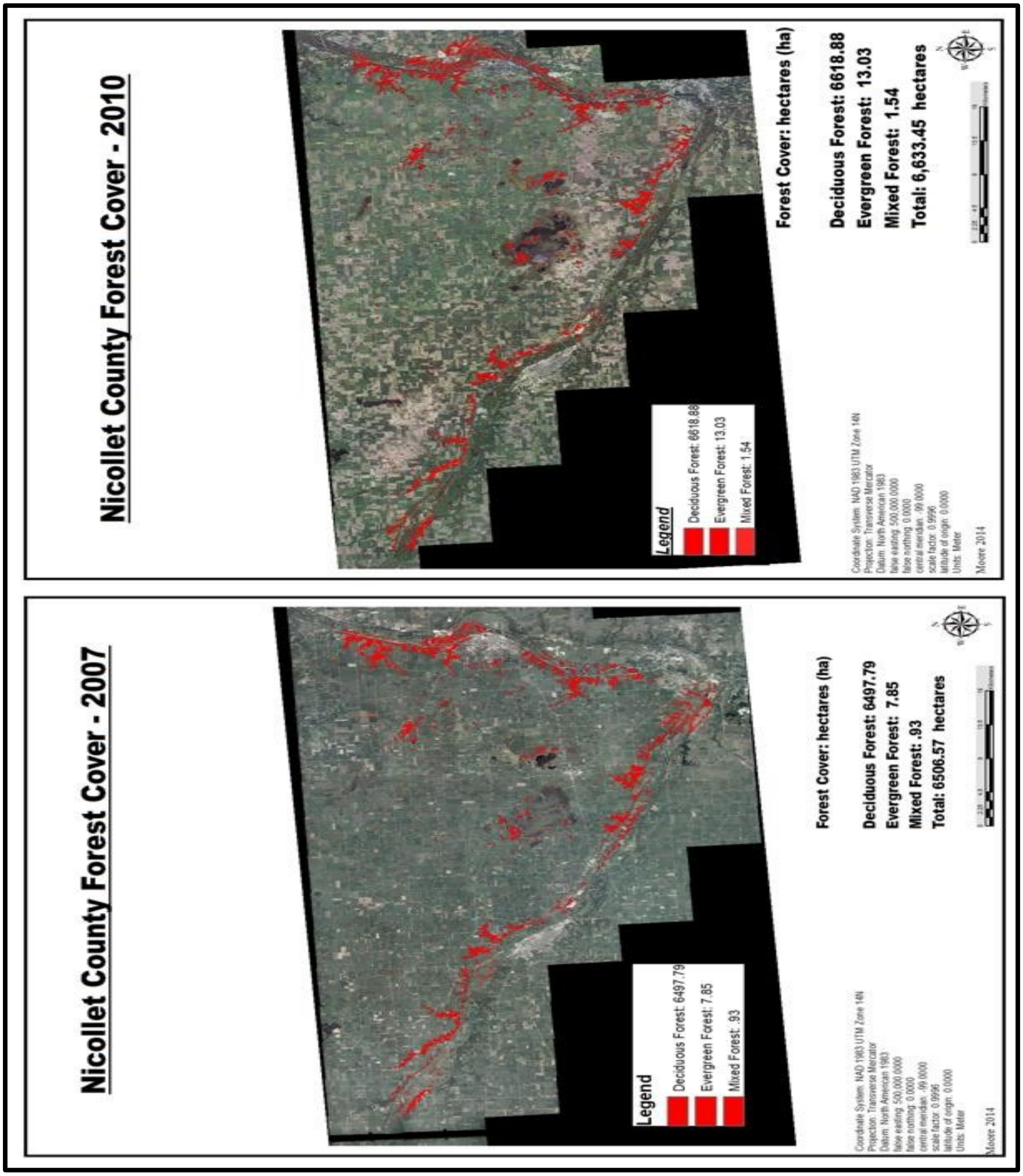


Figure 21a: Multi-temporal remotely sensed data manipulated and displayed in the GIS application ArcMap 10.1. The two data sets compare forest covers in Nicollet County. Nicollet County has much more forest cover but a majority of this cover is isolated to the river corridor. A change was noted in forest cover however with an increase of 126.88 hectares between 2007 and 2010.

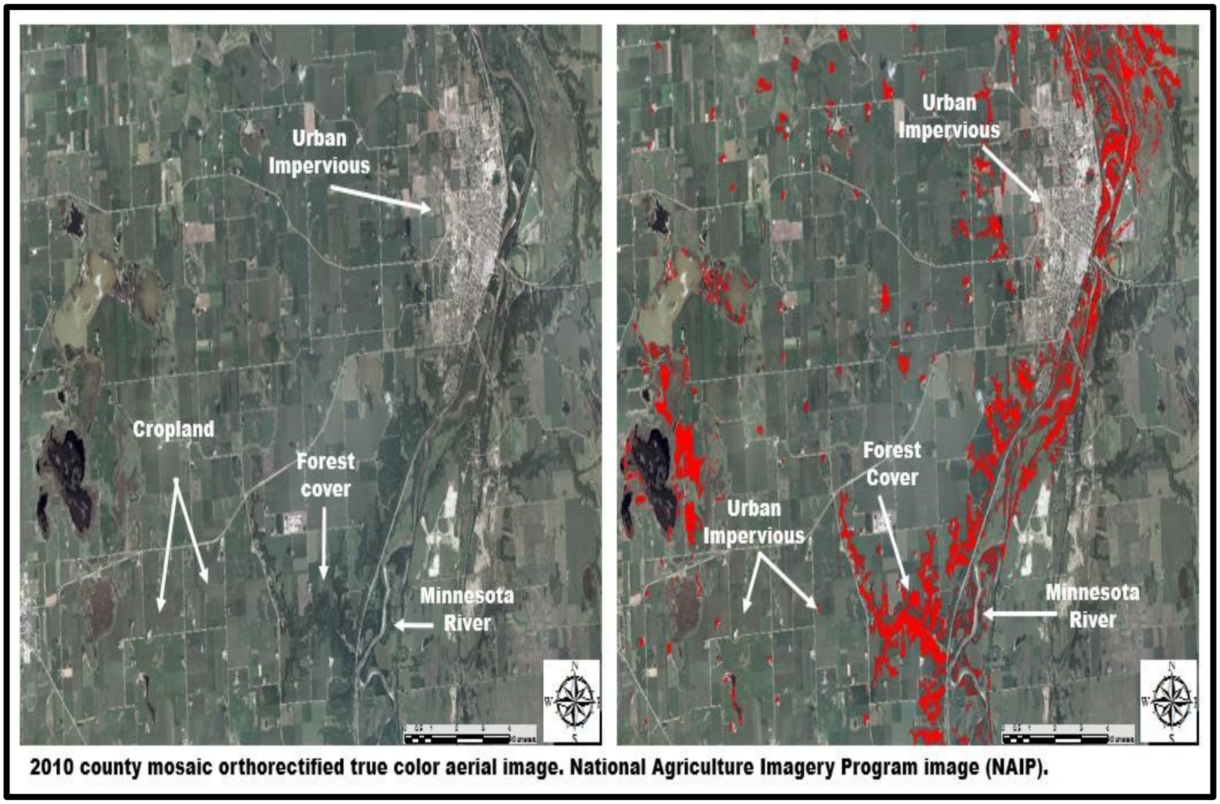


Figure 21b: 1:80,000 scaled orthorectified aerial photo of Nicollet County in 2010. The increased spatial resolution allows for land covers to be discerned more easily. There is much more forest cover in Nicollet County and much of it is continuous and non-fragmented. Like Big Stone County the forest cover is largely found within the river corridor.

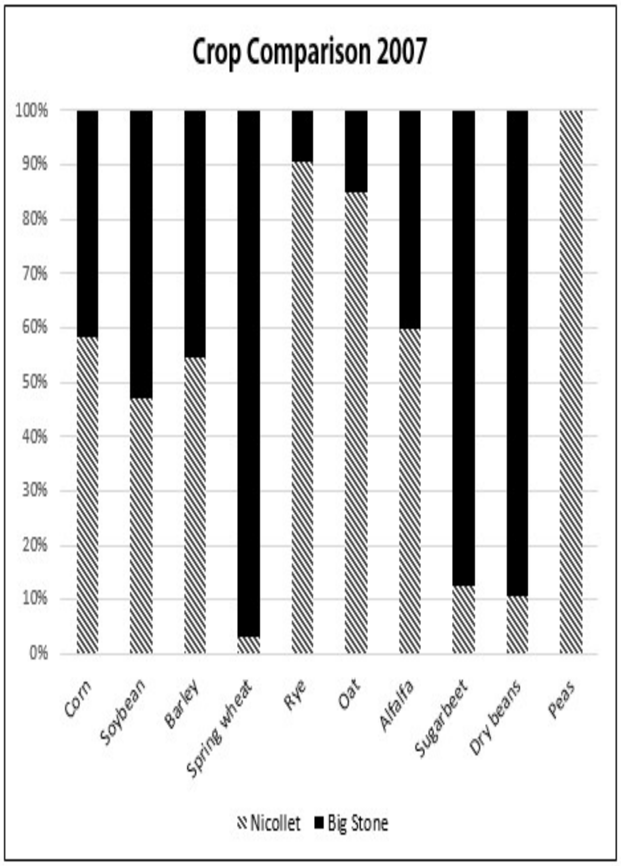
VII. Analysis of Agricultural Patterns

Agriculture is the dominant land cover type seen in this particular Upper Midwest study area. The rich mollic soil dictates that this activity encompasses the area because it provides economic stability to the region. Cultivated lands suffer greatly at the hands of humans as we overuse, over fertilize and repeatedly deplete this rich soil of its native nutrients. These changes to soil composition impact the porosity and draining properties of the soil as well. Landscape attributes have an important effect on WNV disease dynamics and ecology by influencing host and vector presence, behavior, and interactions (Enzewa et al., 2007

As found in the previous analysis there is more forest cover in Nicollet County but other factors will also govern the amount of arable land available for cultivation in each county and in turn how much vector habitat is available. The two sample counties are largely cultivated and also typically produce similar type crops and those crop types are indicative of the climate in the region. Major crops in the area consist of corn, soybean, alfalfa, barley, oats and spring wheat. Many minor crops are also seen in the study area. They consist of sugar beets, sunflowers and potatoes. Although mosquitos can take up breeding in small locations, for this analysis crops were excluded if they were less than 20 acres (8.09 ha) planted. The data suggests that crop type is not a factor in WNV prevalence and therefore will not be addressed. However, the maps are presented using crop type data that was accumulated at the county level. The overriding influence on a disease such as WNV is the amount of cultivated lands in the area.

Figure 21 is a GIS derived map illustrating cultivation in Big Stone County. Figure 22 is a secondary GIS map illustrating a low incidence county and its cultivation, Nicollet County. The years addressed here are 2007 and 2010.

Training data used in this analysis was acquired from the open source data website Cropscape operated and maintained by the USDA National Agriculture Statistical Service (NASS). The data was placed within ArcMap 10.1. For analysis pyramids were created and resampled using the nearest neighbor algorithm. A raster attribute table was created for each data set (2007 and 2010) which allowed for specific crop types to be isolated, hectares analyzed and a map was derived for each county. The data was layered over an orthorectified aerial mosaic of each county for each year. Table 11 is a comparison of crop types between Nicollet and Big Stone counties for the years 2007 and 2010.



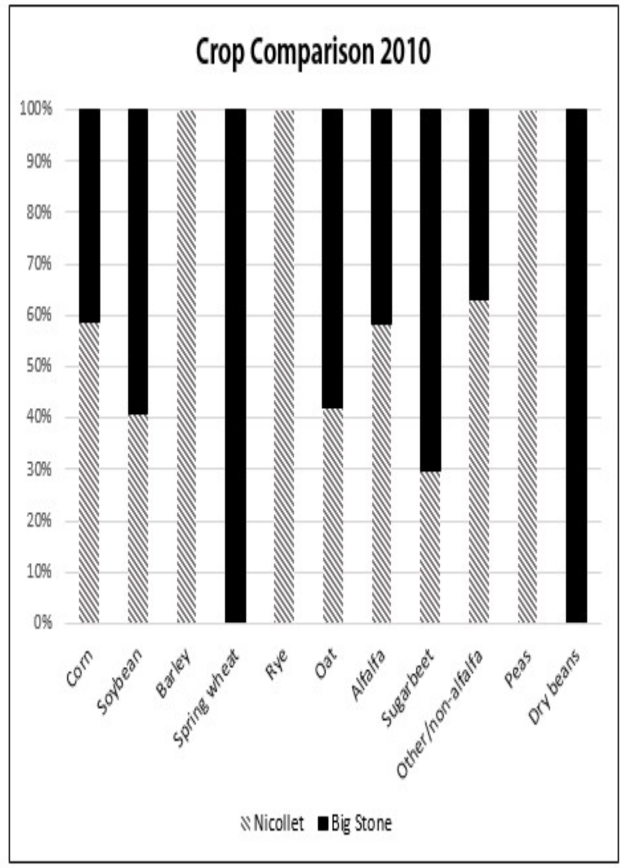


Table 9: Crop comparison tables for Nicollet and Big Stone counties for years 2007 and 2010. Each county exhibits dominant crop types per year and the percentage is variable. Both counties produce large amounts of corn, soybean and alfalfa yearly. Big Stone County produces significantly more spring wheat, whereas Nicollet County routinely produces more peas, rye and barley (USDA NASS, 2014).

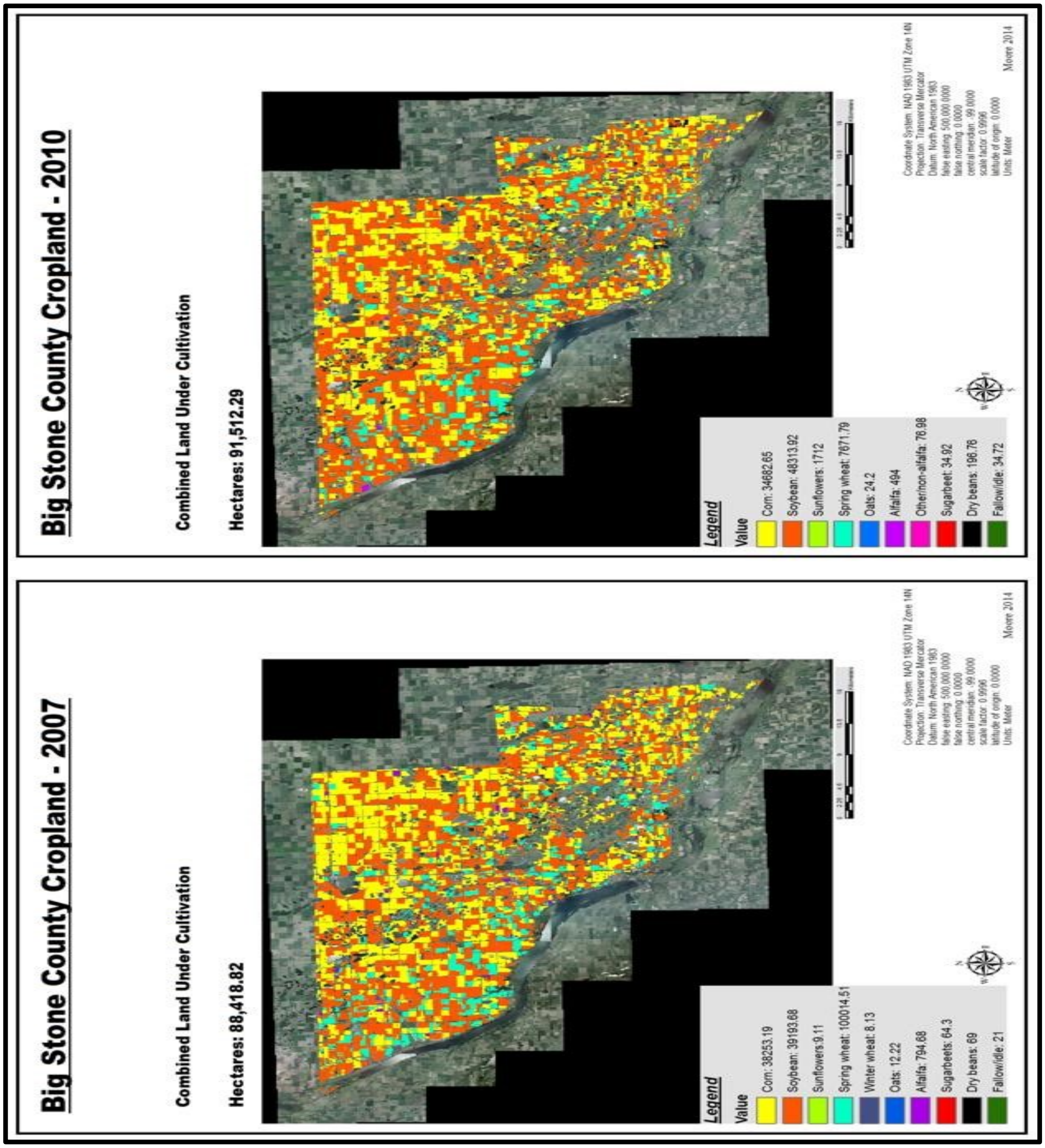


Figure 22: Lands under cultivation in Big Stone County, Minnesota during the years 2007 and 2010. Like most counties in the study area Big Stone is excessively cultivated. An increase in cultivation was seen over the time period. 3,094.07 hectares was gained added by 2010.

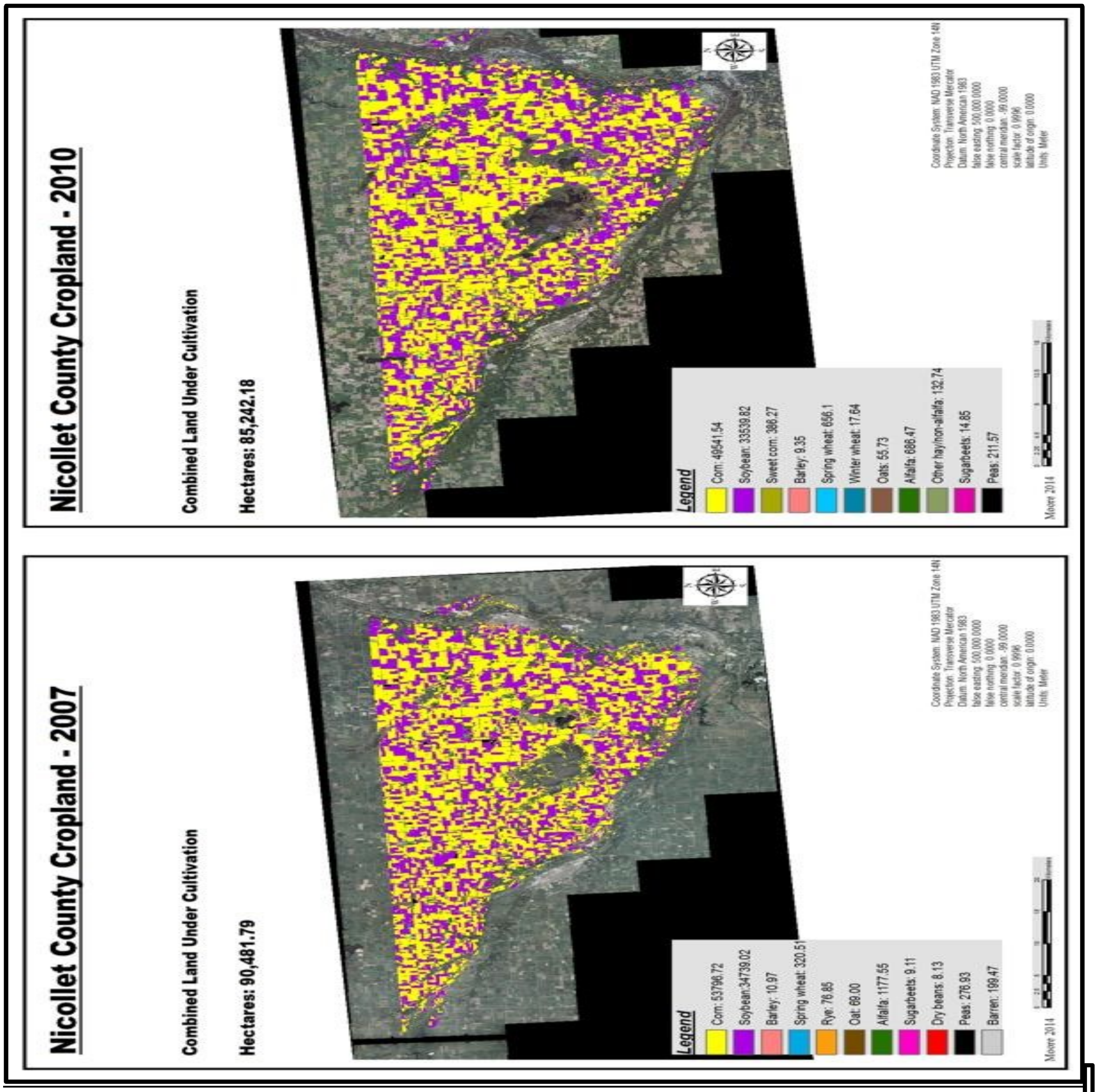


Figure 23: Lands under cultivation in Nicollet County, Minnesota during the years 2007 and 2010. Like most counties in the study area Nicollet County is excessively cultivated. A decrease in cultivation was seen over the time period, with 5,239.61 hectares was taken out of production in 2010.

Discussion

In a rural landscape there lies a lack of urban type infrastructures such as storm drains and tend to be clustered in small town locations. The incidents of WNV are lower in rural areas but so are the population densities. The rural locations that are heavily cultivated present attributes that tend to increase disease prevalence such as water ponding, increased outdoor employment and recreation. Both counties exhibit large areas of cultivation, which inherently cause water ponding, and agricultural ditches with stagnant organic laden water areas are also numerous. The type of cultivation does not seem to play a role as both counties ultimately produce the same crop types yearly. Big Stone exhibits a higher number of WNV cases and this is likely due to the fact that the areas income is derived from agriculture at a higher rate and therefore more people come in contact with vectors in this outdoor employment type. Data obtained from the US Census Bureau

Community Survey 2008-2012 webpage (US Census, 2013). Big Stone reports 13.63% of its population is employed in the agriculture, forestry, fishing, hunting, mining fields. Whereas for the same employment fields in Nicollet County only 4.40% of the population is employed. Nicollet County has nearly as much land under cultivation but the population is largely urban with much larger urban centers than are seen in Big Stone County. This more urban rather than agriculture (farming) lifestyle decreases contact with vectors in Nicollet County it appears.

There is also the factor that residing in an urban location an individual is more protected with county mosquito abatement programs being directed at urban centers and not rural locations.

VIII. Analysis of Open Water Surfaces and Wetlands

Water and most specifically static water bodies such as lakes provide suitable habitat for vector breeding. Water bodies in Minnesota are also highly attractive natural locations to humans. Fishing, boating and other water sports bring humans into direct contact with vector habitats. Big Stone County exhibits large tracks of glacial lakes where Nicollet County has limited open water with one large lake (Swan Lake) and many wetlands. Both counties have wetland locations and these are significant vector breeding habitat sites. Wetland ecosystems fulfill critical ecological roles by providing habitat for resident and migratory organisms, buffering against floods and precipitating sediment from streams, among other services (Mercer et al., 2005). However, they also provide highly suitable habitat for mosquitos (*diptera; Culcidae*), which are insects of major public health concern for their role as vectors of disease and for their well-known nuisance (Victoria, Dario, and Eduardo, 2011) Figures 24 and 25 display lake data for each county. The lake data was overlaid on a US Census department census tract layer to get a specific county area.

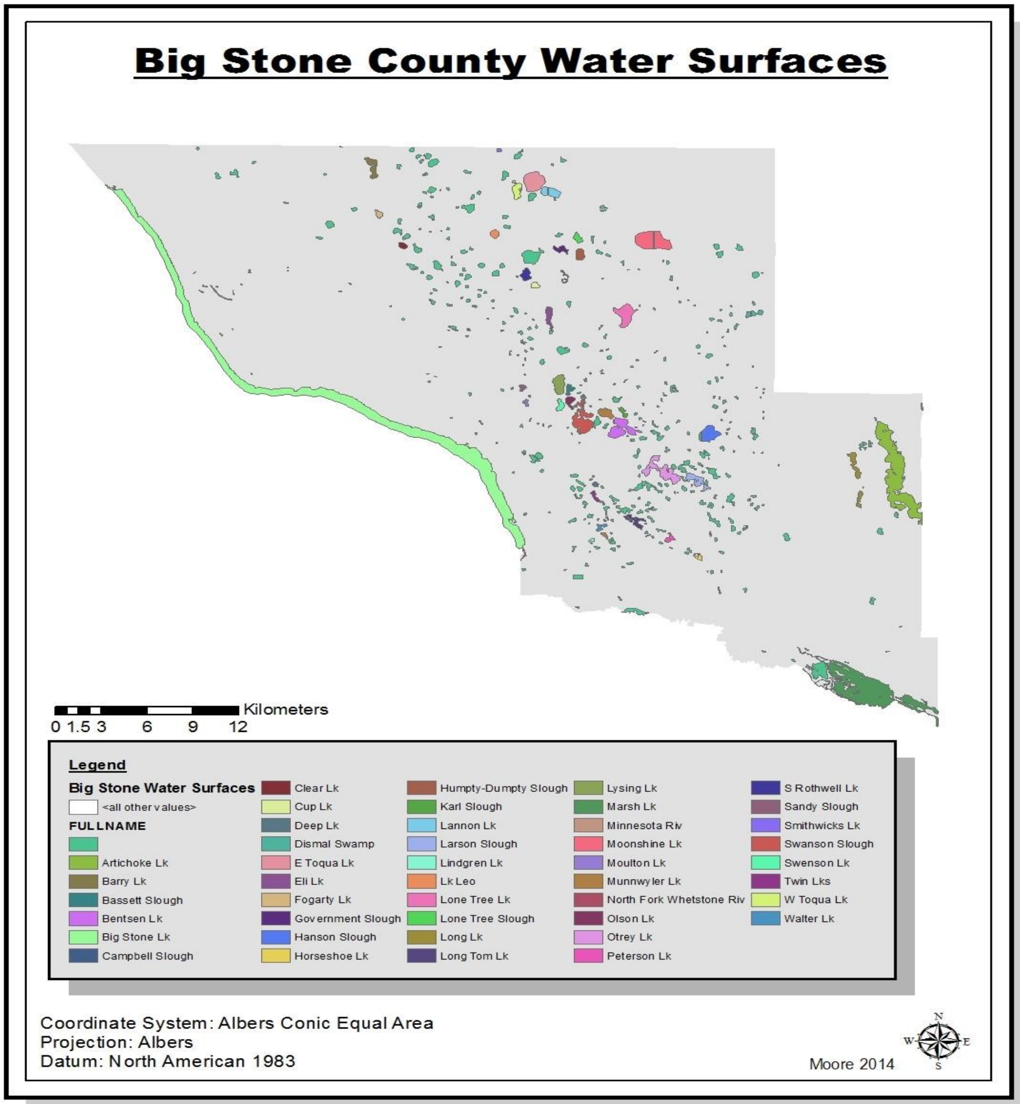


Figure 24: Big Stone County exhibits a large swath of glacial lakes within its borders. The county has a reported 22,603.10 acres of open water.

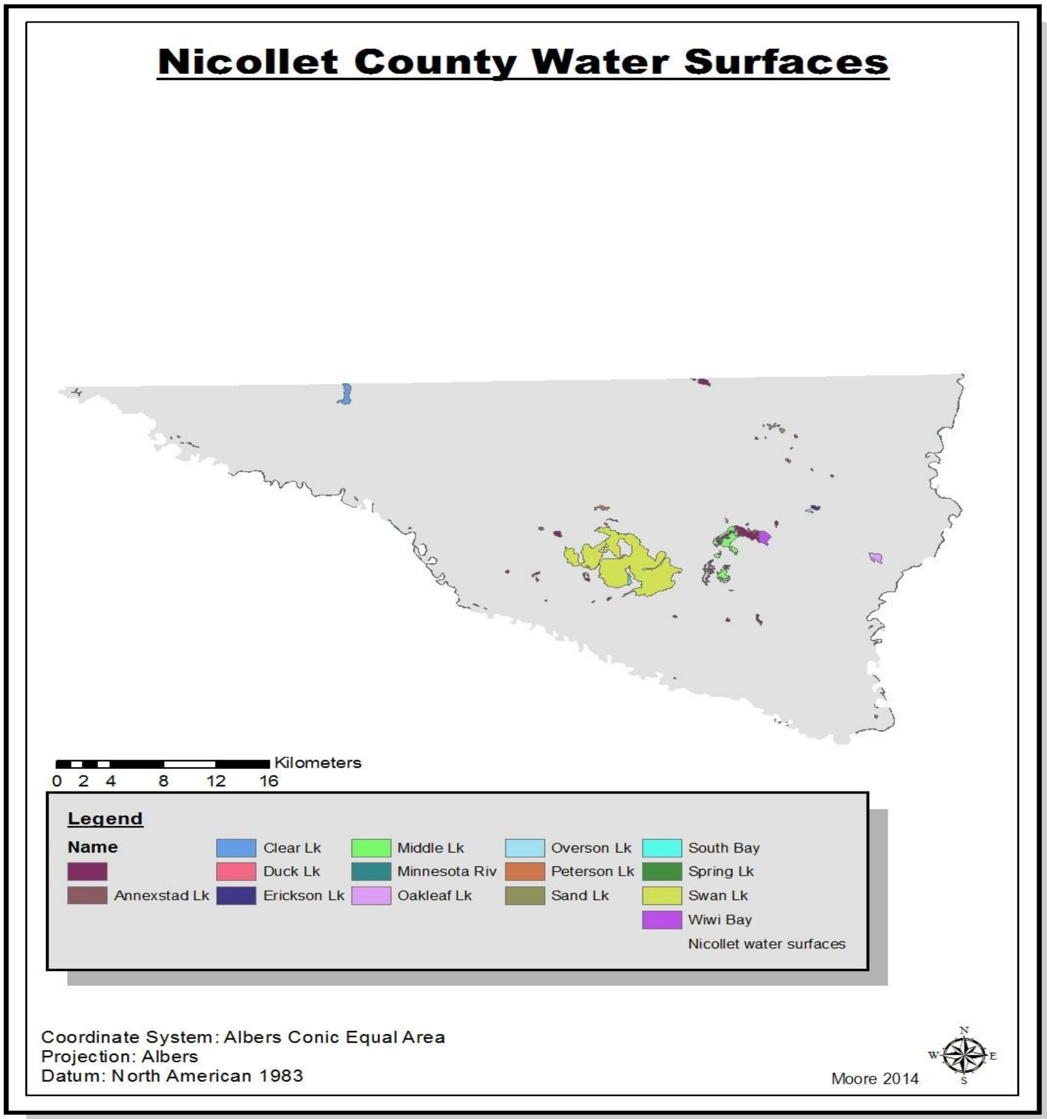


Figure 25: Nicollet County exhibits a smaller amount of glacial lakes with one large lake, Swan Lake. The county has a reported 10,177.21 acres of open water.

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Big Stone County

In wetlands, the abundance of mosquito larvae is often limited by biotic factors, such as predators and competitors (Blaustein and Karban 1990; Blaustein and Margalit 1996; Blaustein 1998; Stav et al., 2000; Mokany and Shine 2003). In addition, the importance of these biotic interactions varies depending on the type of wetland (Chase and Knight, 2003). Three types of wetlands were identified in the study area; mixed, woody and herbaceous wetland ecosystems.

Woody wetlands are defined as areas where forest or shrubland vegetation accounts for 25-100 percent of the cover and the soil or substrate is periodically saturated with or covered with water (NCLD, 1992). These wetlands are important as their water levels fluctuate seasonally and show low levels at the end of the summer season. These types of wetlands are highly susceptible to the effects of drought.

Herbaceous wetlands are defined as areas where perennial herbaceous vegetation accounts for 75-100 percent of the cover and the soil or substrate is periodically saturated with or covered with water (NCLD, 1992). Figure 26a illustrates wetland amounts and locations located within Big Stone County, 2007 and figure 26b depicts locations in 2010. The two data sets were fused and projected over the 2010 orthorectified county mosaics in order to compare gains/losses in figure 27.

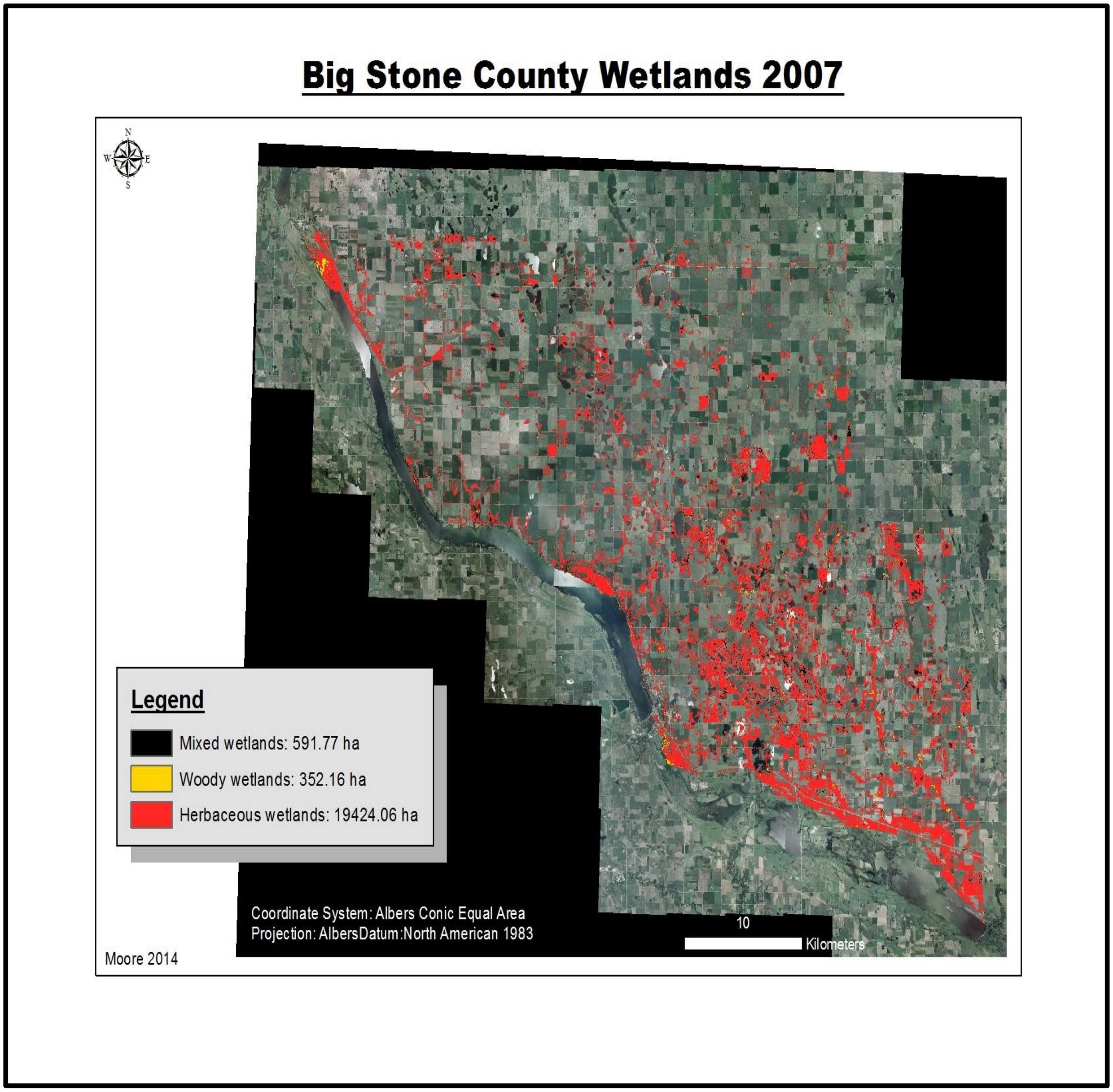


Figure 26a: 2007 wetland locations located within Big Stone County, Minnesota. Total hectares of wetland types were 20,367.99.

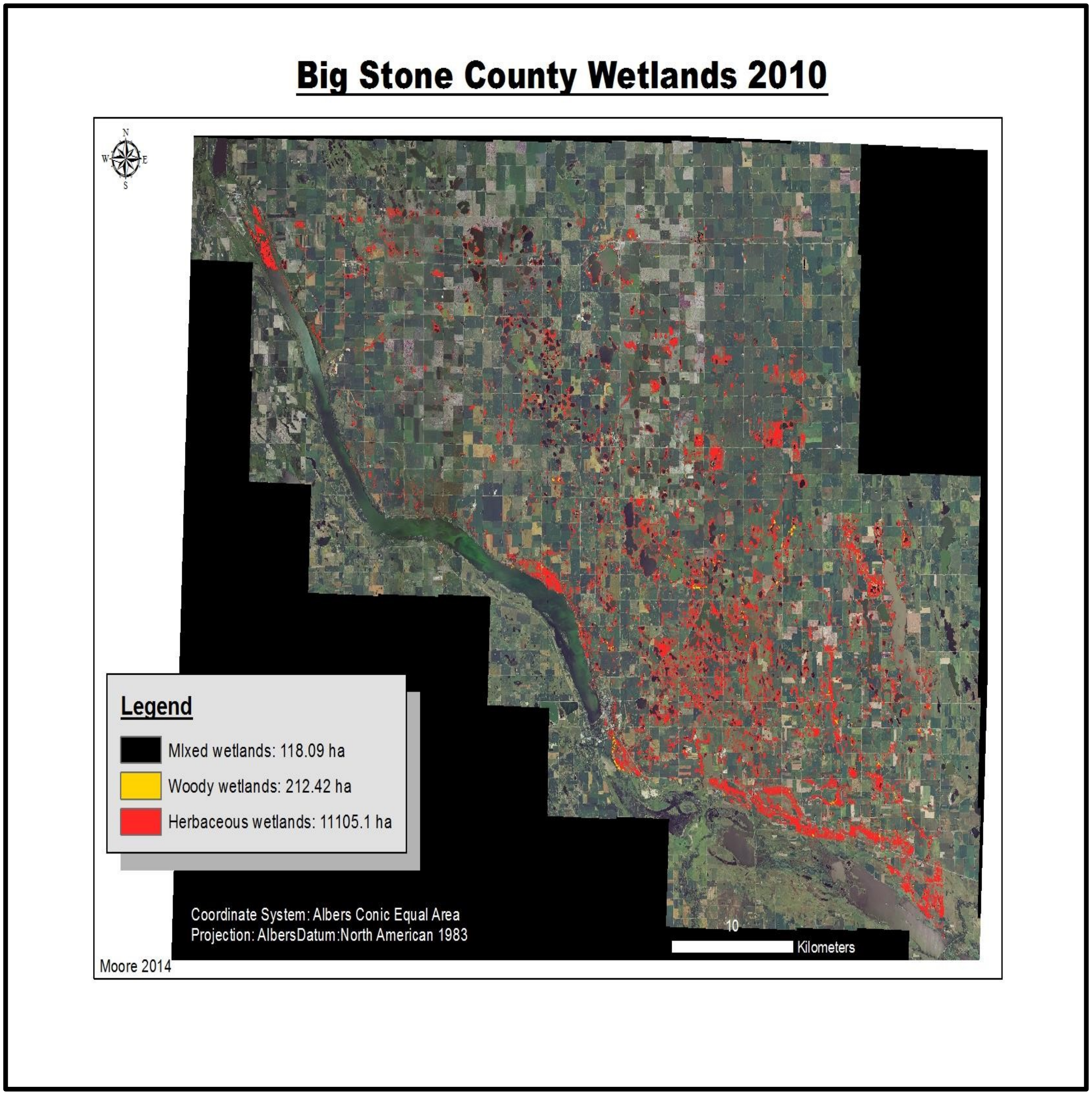


Figure 26b: In 2010 wetlands in Big Stone County noticeably decreased. However, the county still retained more total surface area than Nicollet County. This is most likely a reason for higher prevalence of WNV in Big Stone County, MN.

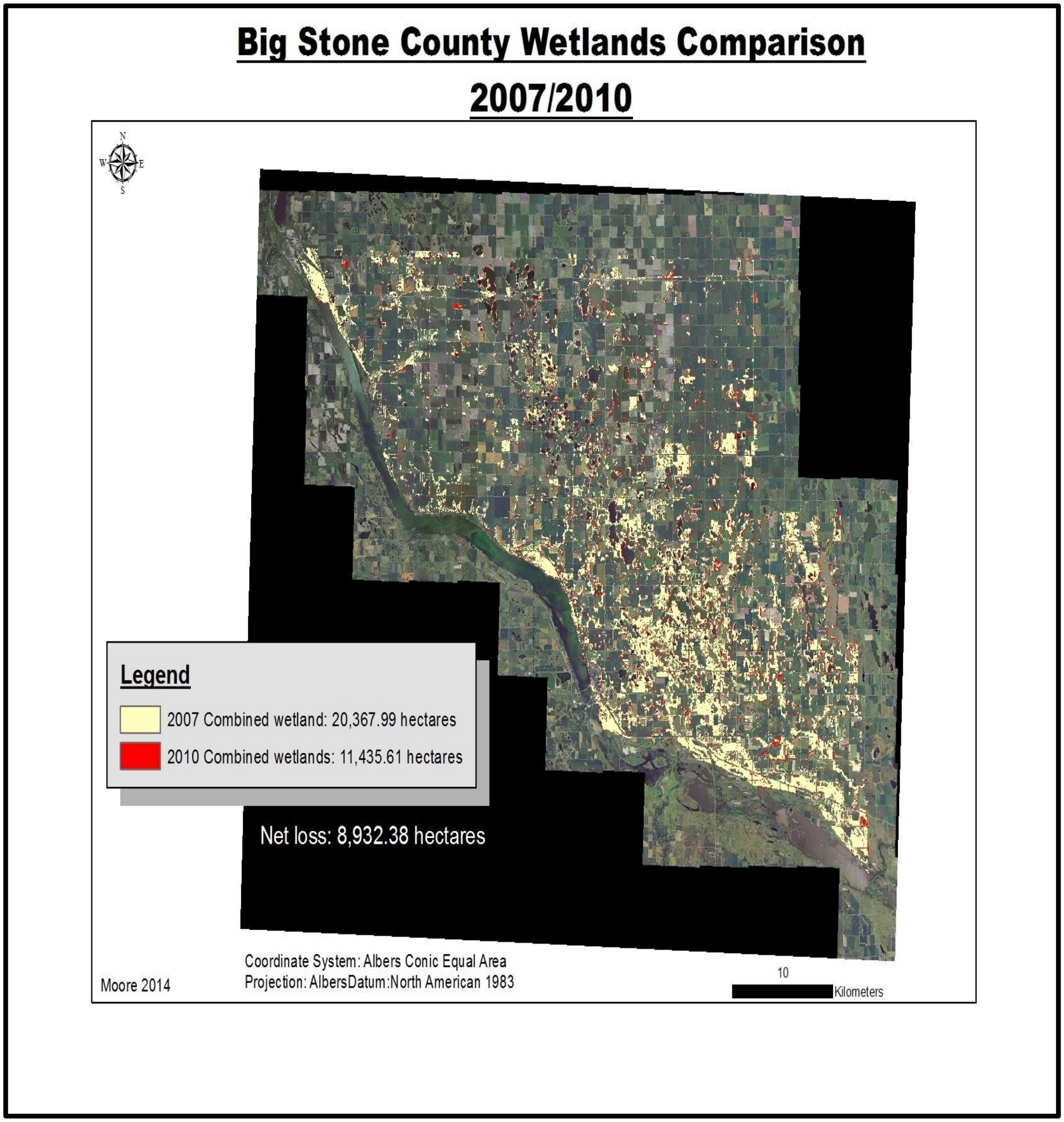


Figure 27: In this figure wetland losses can be noted. Some of this loss can be attributed to abnormally dry conditions but no significant drought took place in the previous years. The loss is primarily the result of humans draining them to increase arable land available for cultivation. Total loss: 8,932.47 hectares.

Nicollet County

The analysis for Nicollet County wetlands produced the same result as seen in Big Stone County. Figure 28a and 28b illustrate wetland locations in the two sample years, 2007 and 2010. Figure 29 illustrates the comparison from 2007 to 2010; a net loss in combined wetland locations/amounts was seen within Nicollet County.

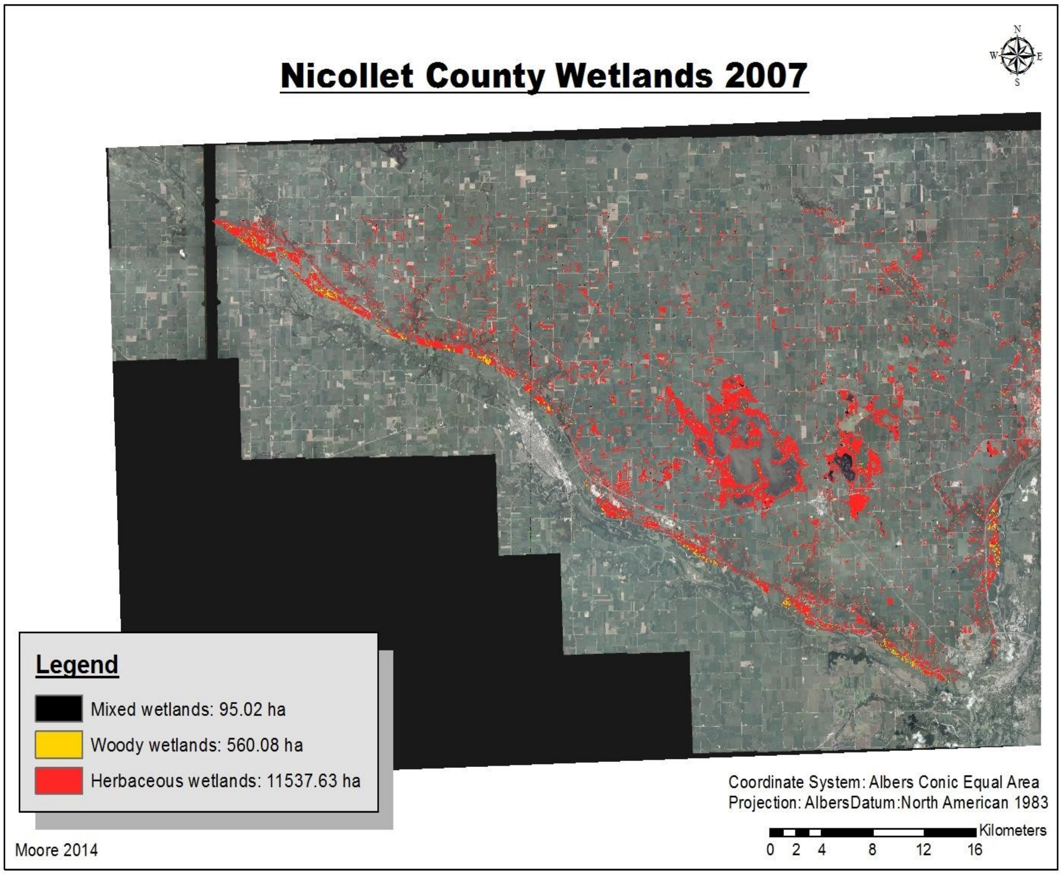


Figure 28a: This figure illustrates a large amount of wetland locations with herbaceous wetlands being the most common type in 2007.

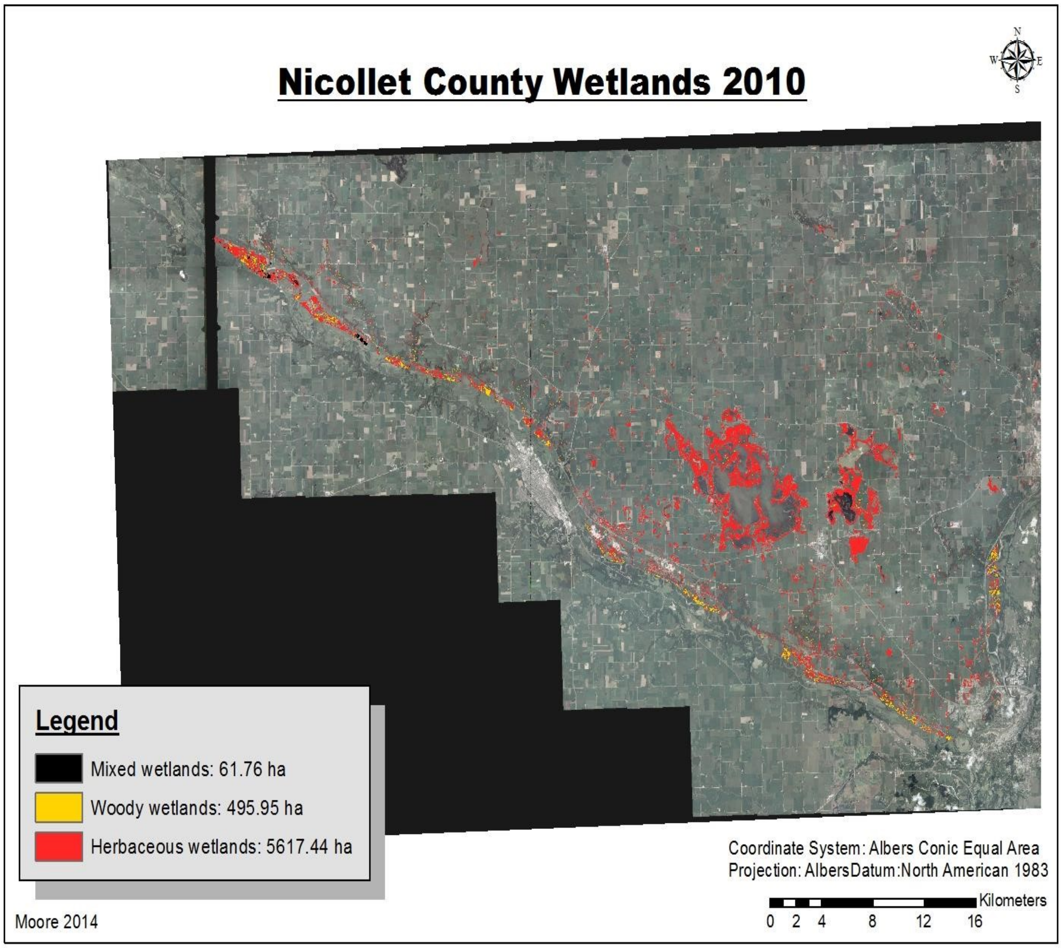


Figure 28b: Nicollet County wetland locations and types in 2010. A significant decrease observed with 6,017.85 less hectares.

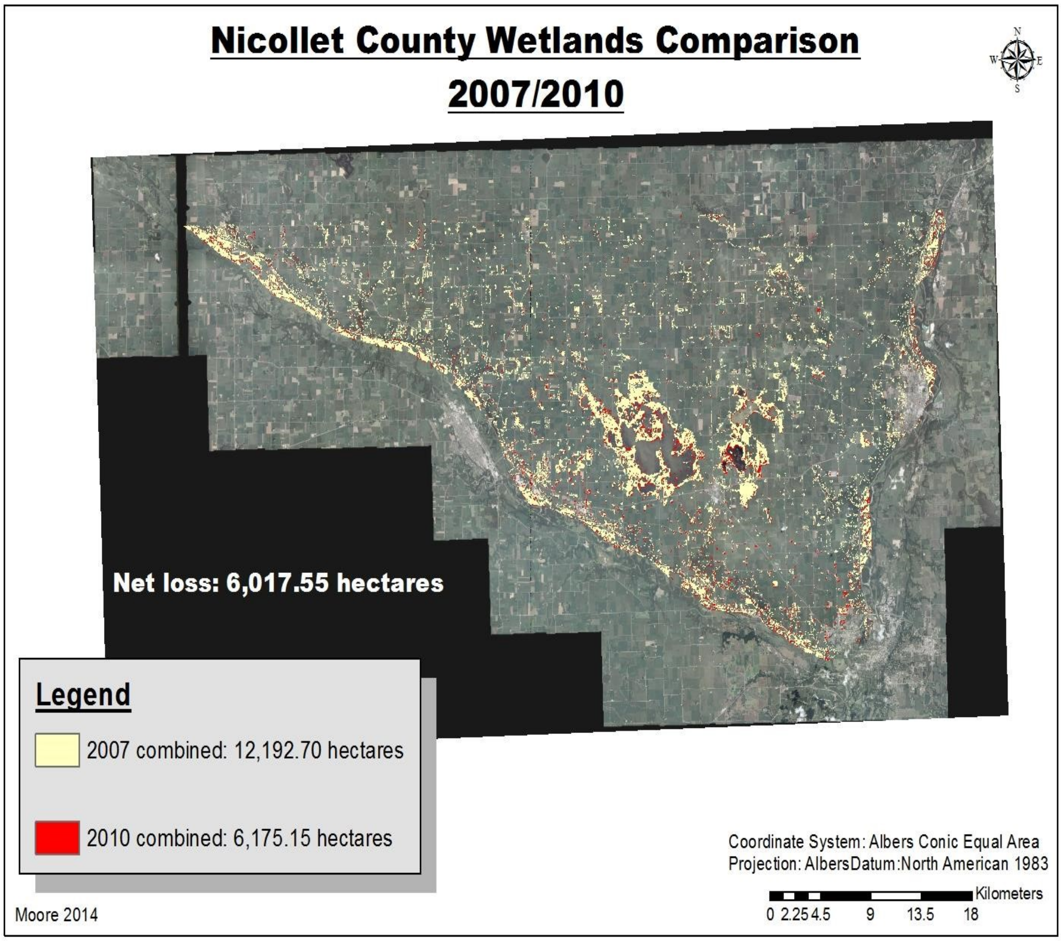


Figure 29: Comparison of wetland locations, types and amount from 2007 to 2010. There was a large net loss of 6,017.55 hectares or a 49.4% decrease in wetland locations. The US Drought Monitor data does not report any impactful drought in the area in 2007 or 2010.

Discussion

Wetland locations are significant repositories and breeding sites for mosquito populations and also attract the avian hosts able to spread WNV quickly and widely. Both counties exhibit significant losses in viable wetland vector habitats. In the outbreak year of

2007 Big Stone County had a relative amount of wetlands totaling 20, 367.99 hectares. Whereas Nicollet County possessed a total of 12,192.70 hectares of combined wetland types. During the outbreak year of 2007 Big Stone County possessed 50.22% more wetland locations than were in Nicollet County. This large difference in available vector habitat in 2007 likely contributed to the higher rate of confirmed WNV cases in Big Stone County. 2007 was also the first year that Nicollet County reported a WNV case. This data suggests that areas with more available vector habitat will likely promote more disease proliferation as seen in Big Stone County, Minnesota 2007. However, as previously stated in chapter one WNV is entangled within a complex system and many attributes play a role. In drought years a decrease may not be seen even with receding wetland surface hectares. This can be attributed to the drought, as it is also impacting vector predators and decreasing their numbers. Drought years may allow for exponential growth in vectors produced because of this competing attribute (Brown, Medlock and Murray, 2014).

IX. Analysis of Soils

The soils of Minnesota are dominated by glacial activity and much of this activity deposited and the percent material is a direct reflection of the soil regimes in the state today. The Wisconsin Glaciation began approximately 75kya and was characterized by multiple pulses creating the landscape in contemporary Minnesota. Mollisols dominate the area and two sub-orders have been isolated due to their inability to freely drain on a consistent basis. Poor drainage for ponding of water over several days which in turn will allow for vector breeding to take place. Aquolls and Aquic udolls present possibilities for ponding are susceptible to compaction and ponding and depending on soil condition can be poorly drained. Aquolls represent soils that are wet and tend to develop in low lying areas where water collects. These can be essential in creating vector habitat from the soil moisture and humidity they create in an area. Adversely these soils can be non-influential in years of significant drought.

Maps were created using GIS for Big Stone and Nicollet counties. The data was obtained from the open source soil data repository operated by the USDA. The Web Soil Survey (WSS) is overseen by the Natural Resource Conservation Service (NRCS) and offers data by entire US, county and state; the area of interest (AOI) can be set by the user. The data is available in shapefile format which can be uploaded and manipulated in ESRI ArcMap 10.1. The data was downloaded and loaded into ArcMap 10.1. The files load all soil types for the county AOI and manipulation was needed.

All Aquolls and Aquic Udolls were isolated and color coded. Soils that are not located in these sub-orders were removed from the raster attribute tables.

These soils were excluded because they promote little ponding and inherently drain well. These soils also are not abundant in the area. Water features were left in the map as a point of reference and allow for a better understanding of soil placements in the county.

Figure 29 is a digital representation of Big Stone County soils that bear significance to this study. Within the soils selected aquolls represent 60.87% of the soil types. The rolling hill topography in the study area makes for easy development of aquolls soils. Most of the soils have had a vegetation of grasses, sedges, and forbs, but a few also have had forest vegetation. In the United States, aquolls are most extensive in glaciated areas of the Midwestern States where the drift or loess was calcareous (NRCS, 1999). Aquic soil regimes make up 26.08% of the soils in the county and exhibit wet saturated characteristics that can promote ponding. The soils located within this county exhibit a high probability of being able to be used as vector habitat. The soils isolated as high risk makeup 86.95% of the soil types in the county.

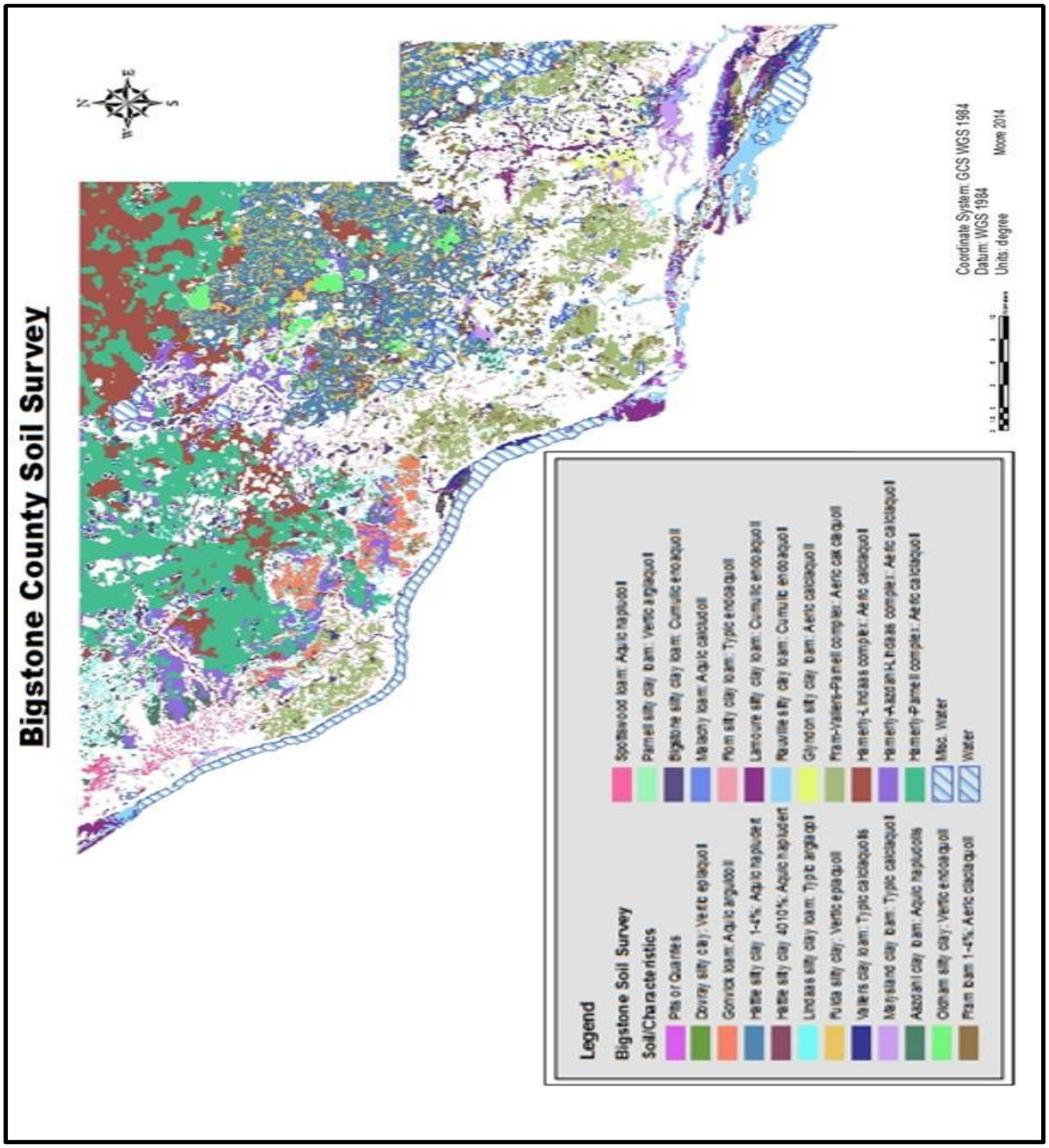


Figure 30: GIS derived map showing soils in Big Stone County that represent possible vector habitat sites. These soils exhibit saturated, wet, ponding characteristics in the study area.

Soils in Nicollet County are similar to those found in Big Stone County as they were essentially developed during the same glaciation events. The difference lies in the agricultural practices that may differ from county to county. Nicollet County exhibits a wider array of the selected soils, aquolls and aquic udolls with several different types. 28 total soils were isolated whereas only 23 were able to be isolated in Big Stone County. 67.86% of the soils are aquolls, 25% of the soils were determined aquic in nature. Of the soils in the county 92.86% have the possibility of creating vector habitat by ponding or due to being supersaturated from intense rainfall. Figure 30 is a digital representation of high risk soils located within Nicollet County.

The data reflects that Nicollet County has more of the high risk wet ponding type of soils that could create vector preferred habitats. Irrigation is not common in the area and tiled field data is sparse and not credible enough to use at this time. Drought extent may be influencing the presence of WNV in the counties as well. Nicollet County having a higher percentage of high risk soils and lower prevalence of WNV indicates that soils regimes may exert little total influence on vector abundance in this specific ecosystem.

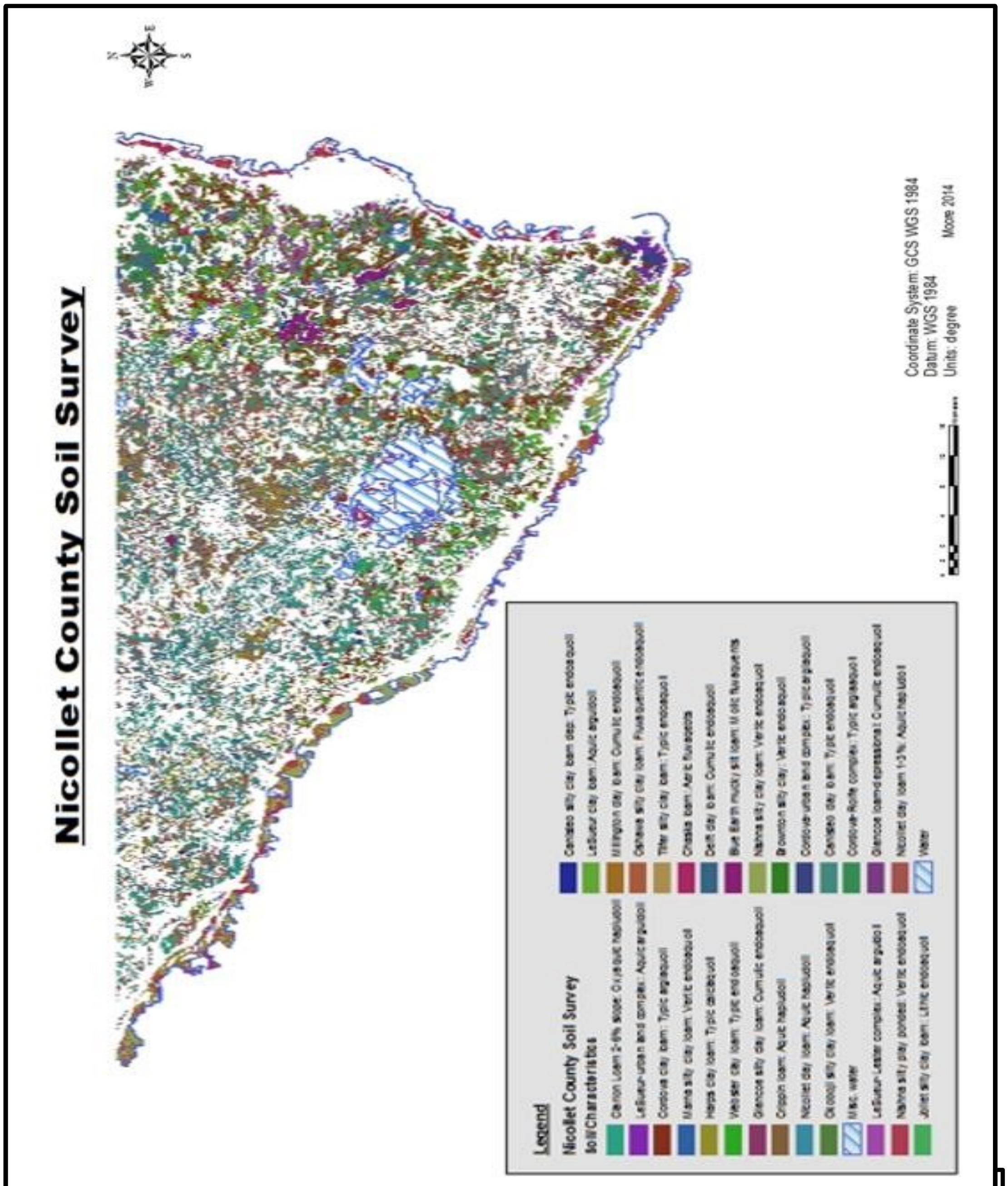


Figure 31: GIS derived map showing soils in Nicollet County that represent possible vector habitat sites. These soils exhibit saturated, wet, ponding characteristics in the study area. Nicollet County possesses more high risk soils than the higher WNV prevalent Big Stone County.

X. Final Discussion

Land cover, climate and population all play an integral role in the prevalence of WNV and other environmental diseases. The complexity of some causal pathways makes attribution difficult. Recent climate change might have contributed (via changes in temperature, rainfall, soil moisture, and pest and disease activity) to altered food yields in some regions (Zell, 2004). The data for the two county comparisons shows that temperature, wetland amount and agricultural practices likely have the most influence over vector abundance. When a warmer March with significant amounts of days over 50^{o}F is seen WNV prevalence is high and very active in the later summer season. Precipitation in the rural locations plays a role in wetland recharge, ponding in cultivated fields and in artificial water containers left out for farm animals to utilize.

The overall result proves that the dispersion of environmental disease such as WNV is ultimately just a part of the larger more complex system that is dominant in an ecosystem. Some factors appear to exert a large influence such as temperature and wetland amounts but smaller less impactful variables such as soil type, soil compaction, drought, elevation and precipitation also appear to exert some level of influence on vector abundance. Further research concerning these factors can be completed if more resources were available such as mosquito trapping, dip netting, bird collection, equine testing, mosquito testing and more concise population demographic information such as town of residence, age and career type of victims were available.

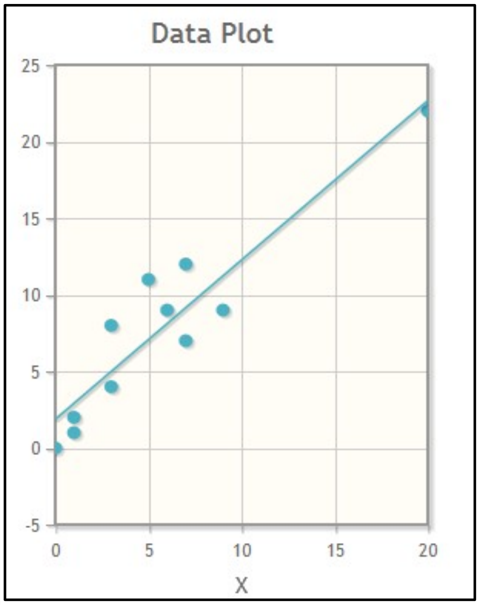
Chapter Five

Discussion and Conclusions

I. Results

The results indicate that WNV like many similar environmental diseases are extremely complex and dynamic in nature. The disease is essentially part of a system and therefore dependent on many parts of that system. Land cover, climate and population all play an integral role in the prevalence of WNV and other environmental diseases but defining a single cause is difficult. The complexity of some causal pathways makes attribution difficult. Recent climate change might have contributed (via changes in temperature, rainfall, soil moisture, and pest and disease activity) to altered food yields in some regions (Zell, 2004).

The attribute with data that suggests the most impact is seasonal temperature variation and is accurately identified in outbreak years. Linear regression displays a strong correlation and is displayed in figure 26 below. The Pearson's R value of 0.93 allowing the conclusion to be made those years with more days above 50^0F in March influences the amount of WNV cases.



Mean of X	Mean of Y	Std Dev of X	Std Dev of Y	Pearson's r
5.636	7.727	5.573	6.23	0.93

$R^2 = .86$

Figure 32: Illustrates a strong correlation between temperature and WNV cases.

Some factors exert a large influence such as temperature and wetland amounts but smaller less impactful pieces such as soil type, drought, elevation and precipitation also exert some level of influence on vector abundance. Further research can be completed using these factors if more resources were available such as mosquito trapping, bird collection, equine testing, mosquito testing and more concise population demographic information such as town of residence, age and career type of infected individuals was available.

II. Data Limitations

Data limitations in this project were significant in that field data from mosquito traps, mosquito larvae dip netting, and mosquito reservoir pools were not available. Contact was made with Minnesota Department of Health (MDH) to assess whether locations (town/city) of individuals confirmed to have WNV could be obtained. MDH advised that due to the federal regulation of the Health Insurance Portability and Accountability Act (HIPAA) of 1996 that they could not release such locations. This severely limited a spatial analysis of cases within county borders. The only accessible WNV case data is vague and shares only the county in which the case was confirmed. This however does not include whether that individual contracted the virus elsewhere and transported it to his/her home county of residence or where within the county the disease was contracted.

Other limitations were found with remotely sensed data sets as well. Digital format crop data is sparse and hard to acquire prior to 2006 for the study area. County crop counts exhibit a disclaimer that error may be as high as 10% in some years. The US Department of Agriculture data was considered the most accurate, and for Minnesota, no data exists prior to 2006. Since, an outbreak year was seen in 2007 and data was available for this event and was utilized in this project. One limitation constrained the whole outcome of the study itself. As MDH advised it is extremely difficult to make predictions with such small data sets.

As outlined in the previous chapters, Big Stone County had the highest reported number of cases with 12 over a 10 year period per the Centers for Disease Control and Prevention.

III. Research Implications

Flaviviral infection is a significant threat and encephalitis due to their infections is a cause of major concern with recurrent reports of epidemics from different realms of the globe. *Flavivirus* genus contains more than 70 viruses of which some of the prominent members are dengue virus (DENV), Japanese encephalitis virus (JEV), tick-borne encephalitis virus (TBEV), West Nile Virus (WNV), Hepatitis C virus (HCV) and yellow fever virus (YFV). They are well-known human and animal pathogens, constituting a global public health challenge with more than a billion people infected yearly (Nazmi et al., 2014).

The impact of disease such as WNV can be significant and outbreaks are recurrent within the US. Several outbreak years have been seen in Minnesota and most certainly will be seen in the future as well. The climate is changing and environmental diseases are becoming more prevalent as conditions improve for diseases such as WNV to proliferate. There is no doubt that we are presently experiencing progressive global warming due to the increased production of greenhouse gases. Global surface temperatures have increased by approximately 0.3- 0.6°C during the 20th century (Intergovernmental Panel on Climate Change, 2013). Variation in the incidence of vector-borne diseases is associated with extreme weather events and annual changes in weather conditions.

Moreover, it is assumed that global warming might lead to an increase of infectious disease outbreaks (Zell, 2004). Changes such as this produce great challenges for public health departments to predict and mitigate environmental diseases. The diseases are complex and with so many factors impacting the prevalence of viruses such as WNV the task is extremely difficult to assess risk. The complexity of not yet fully understood pathogen transmission dynamics with numerous variables might be an explanation of the problems in assessing the risk factors (Zell, 2004). The complexity and dynamics of these diseases outlines the implications research such as this has. The disease is variable and that variability ranges from region to region and studies such as this are invaluable for creating a complete picture of disease prevalence and risk. Knowledge is inevitably power and the more research projects that can be completed the better the understanding of such a complex subject can be.

IV. Conclusions

Sociologists and geographers studying health and illness have, in recent years, produced a significant body of work that critically examines changes within the field of public health (Williamson, 2004). One of those major changes includes the types of data used and the manipulation of that data. Remote sensing has become an integral part of public health studies that involve such things as environmental diseases. The manipulation of the data using GIS has been a staple of public health research but recent years have seen an exponential growth in computer programs being devised that create more and better maps.

The use of these data sources in this project allowed for a better and more comprehensive study to be undertaken. The visualization of data along with text descriptions allows the reader to make connections in the data that may have gone unnoticed previously. The data suggests that the overriding factor in the prevalence of WNV is temperature for this region at this time. Many other factors were analyzed for their impact and all appeared to have smaller overall impacts compared to temperature. In conclusion the attribute that can be isolated in this project as the driver of increased WNV cases within the population is temperature. Continued climate change in the area will cause temperatures to rise and therefore WNV will grow in prevalence as a direct result of climatic temperature changes.

Continued vigilance by research professionals to produce system based and multiple attribute projects will enable an evolution of understanding in the dynamic field of landscape epidemiology. It is currently known that WNV has the potential to mutate, to adapt into novel environments, to cause disease with high morbidity and mortality, and to cause large outbreaks. It is more than likely to remain a serious public threat in the next years. Enhanced human and animal surveillance, awareness of the medical staff and public, and mosquito control measures are necessary, while the development of effective drugs and vaccines is also very important. Furthermore, studies on environmental parameters will enable the better understanding of the factors that play a role for the virus emergence, establishment and wider dispersal, enabling even the prediction of future outbreaks (Papa, 2013).

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