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An examination of the effect of landscape pattern, land surface temperature, and socioeconomic conditions on WNV dissemination in Chicago

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Abstract This paper developed an approach by the synthesis of remote sensing, landscape metrics, and statistical methods to examine the effects of landscape pattern, land surface temperature, and socioeconomic conditions on the spread of West Nile virus (WNV) caused by mosquitoes and animal hosts in Chicago, USA. Land use/land cover and land surface temperature images were derived from Terra's Advanced Spaceborne Thermal Emission and Reflection Radiometer imagery. An analytical procedure using landscape metrics was developed, applying configuration analysis of landscape patterns in the study area. The positive reports of mosquitoes and animal hosts for WNV in fall, 2001–2006, were collected from the Cook County Public Health Department. Forty-nine municipalities were found to have WNV-positive records in mosquitoes and animal hosts in fall 2004. Socioeconomic data were obtained from the 2000 US Census. Statistical analysis was applied to WNV data in fall 2004 to identify the relationship between potential predictors and WNV spread. As a result, landscape factors, such as landscape aggregation index and the urban areas and areas of grass and water, showed strong correlations with the WNV-positive records. Socioeconomic conditions, such as the population over 65 years old, also showed a strong correlation with WNV-positive records. Thermal conditions of water showed a less but still considerable correlation to WNV-positive records. This research offers an opportunity to explore the effects of landscape pattern, land surface temperature, and socioeconomic conditions on the spread of WNV caused by mosquitoes and animal hosts. Results can contribute to public health and environmental management in the study area.

Keywords West Nile virus · Landscape pattern · Land surface temperature · Socioeconomic conditions · Chicago

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Introduction

West Nile virus (WNV) infection has attracted the attention of public health departments and related organizations in America since the WNV first appeared in New York in 1999. It has been rapidly disseminated to the west, south, and

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northern parts of the country in the following 3 to 4 years (Centers for Disease Control and Prevention 2002). The cases of WNV disease in the whole nation increased and peaked in 2003 (MMWR 2005). Mosquitoes, birds, blood transfusions, organ transplants, and breast milk are believed to contribute to the spread of WNV (Komar 2003; Hayes and O'Leary 2004). The spread of WNV show unique distribution patterns in various study areas (Komar 2003; Hodge and O'Connell 2005; Rainham 2005; Ruiz et al. 2007). Environmental determinants such as the presence of animal habitats, temperature, and climate play important roles in WNV dissemination in North America (William et al. 2006).

Mosquitoes from the genus *Culex*, in particular the species *Culex pipiens*, are the vector of WNV from birds to birds and birds to humans. *Culex* species appear to prefer some land use and land cover (LULC) types (e.g., wetlands and specific grasslands) than some others (e.g., exposed dry soils). Mosquitoes in the canopy site were believed to possess more infections than those in the subterranean and ground sites (Anderson et al. 2006). Wetlands and stormwater ponds, especially those under heavy shade, provide an ideal environment for mosquito development. Ponds with plenty of sunshine and a shortage of vegetation are believed to be a poor environment for mosquitoes growing (Gingrich et al. 2006).

Land surface temperatures (LSTs) reflect surface–atmosphere interactions and energy fluxes between the ground and the atmosphere (Wan and Dozier 1996). Solar radiation and LST are important parameters for analysis of urban thermal behavior (Aguiar et al. 2002; Liu et al. 2006). LST has been used as an important indicator to examine the urban atmosphere and to model urban climate (Voogt and Oke 1997; Jacob et al. 2002; Voogt and Oke 2003). Characteristics of natural and human-involved patches have ecological implications at various spatial levels and influence the distribution of habitats and material flows (Peterjohn and Correll 1984; Turner 1990). Land use and land cover patterns are regarded as an important determinant of ecosystem function and can be considered as the representative of in situ landscape patterns (Bain and Brush 2004). LULC categories are linked to distinct behaviors of the urban thermal environment (Liu and Weng 2008; Weng et al. 2004; Voogt and Oke 1997).

To understand patterns and processes in a heterogeneous landscape, one must be able to accurately quantify the spatial pattern and temporal change (Wu et al. 2000). In recent years, a series of landscape metrics have been developed to characterize the spatial patterns and to compare ecological quality across the landscapes (O'Neill et al. 1988; Riitters et al. 1995; McGarigal and Marks 1995; Gustafson 1998). Software has been developed to calculate the metrics, such as FRAGSTATS (McGarigal et al. 2002).

Remote sensing (RS) and geographic information system (GIS) technologies have been broadly applied in public health study and related issues like urban environmental analysis (Sannier et al. 1998; Hay and Lennon 1999; Wang et al. 1999; Weng et al. 2004; Herbreteau et al. 2007). These researches include diverse epidemiological issues, such as parasitic diseases and schistosomiasis by using RS and GIS as an exclusive source of information for studying epidemics. The potential of thermal infrared (TIR) remote sensing data have been shown to provide valuable temperature information (Luvall and Holbo 1991; Quattrochi and Ridd 1998; Owen et al. 1998; Hirano et al. 2004; Weng et al. 2004). A series of satellite sensors have been developed to collect TIR data from the earth surface, such as HCMM, LandSat Thematic Mapper(TM)/Enhanced Thematic Mapper Plus (ETM+), Advanced Very High Resolution Radiometer, and Thermal Infrared Multispectral Scanner. These TIR sensors may also be utilized to obtain LST and emissivity data of different surfaces with varied spatial resolutions and accuracy. These LST and emissivity data have been used in the analysis of the temperature–vegetation abundance relationship, drought evaluation, modeling of urban surface temperatures with surface structural information, and forest regeneration detection (Boyd et al. 1996; Voogt and Oke 1997; McVicar and Jupp 1998; Wan et al. 2004; Weng et al. 2004).

Research background

Research finds that natural environmental constraints like climatic parameter have significant effects on the transmission of WNV (Dohm and Turell 2001; Dohm et al. 2002). Higher temperatures were believed to contribute to the distribution of WNV throughout North America, and WNV dissemination were significantly related to average summer temperatures from 2002 to 2004 in the USA (Reisen et al. 2006). WNV was not evident in most mosquitoes in cool temperatures (Dohm and Turell 2001). The infection rates of WNV were significantly related to the incubation temperatures chosen (Dohm et al. 2002). Temperature affects replication of mosquitoes during the incubation period (Whitman 1937). The vector capability of specific mosquito species increases with the increase of temperature. In the fall, some mosquito species tend to hibernate and are in developmental diapauses. They prefer plant feed instead of blood feed (Marfin et al. 2000; Komar 2003). In general, when temperature cools down in fall, some mosquito species and many other animals have not started to hibernate by this time, and birds intend to migrate later (Marfin et al. 2000; Komar 2003). This time table is not optimal, but there is sufficient time to explore the spread of WNV caused by mosquitoes and animal hosts in urban areas. The measurements of land surface temperatures during the fall season would provide clues about how the local temperatures influence the virus spread (Komar 2003).

Human-related activities, such as traveling, have significant effects on WNV dissemination. The oviposition patterns of mosquito species were significantly different at urban and rural sites since oviposition activity of mosquitoes reached a peak in the evening and morning in urban areas but it did not have an obvious morning peak in rural areas (Savage et al. 2006). Scientists believed that flooding created by human activities such as logging rather than rainfall caused the increasing abundance of mosquitoes in many wet locations (Balenghien et al. 2006). Inner suburbs were found to have the highest incidence of WNV illness in Chicago, and the characteristics of neighborhoods were believed to be more important than the geographic locations where the illnesses were found in the same study area (Ruiz et al. 2007).

The integration of remote sensing and GIS contributes to the study of physical and environmental factors influencing public health, such as the factors related to the transmission of the virus: mosquito habitat, energy exchange, and land surface temperature (Liang et al. 2002; Rogers et al. 2002; Weng et al. 2004). Satellite imagery has been used to monitor potential disease risks all over the world (Anyamba et al. 2006; Zou et al. 2006). The researchers (Anyamba et al. 2006) analyzed the possible effects of El Niño/Southern Oscillation-related climate anomalies on the disseminations of epidemics all over the world, including West Nile virus based on the study of remotely sensed data. The extreme climate conditions were believed to affect mosquito abundance and elevate the risk of WNV in that area in the near future (Anyamba et al. 2006). Zou et al. (2006) mapped potential habitats of mosquito larvae, a main vector in the transmission of WNV, in the Powder River Basin of north central Wyoming by the analysis of Landsat TM and ETM+ imagery and GIS data. The results indicated that coalbed methane water caused a significant increase of mosquito larval habitats from 1999 to 2004 in the study area.

Many researchers have examined and documented the factors associated with WNV transmission all over the world (Anderson et al. 2006; Balenghien et al. 2006; Gingrich et al. 2006; Ruiz et al. 2007), but the study of the influences of landscape patterns, land surface temperatures, and socioeconomic conditions on WNV dissemination is still undergoing. This study aimed to improve the understanding of how landscape, land surface temperatures, and socioeconomic conditions together influence WNV dissemination in the urban context and to assess the importance of environmental factors in the spread of WNV. The study also determined whether LULC types, LSTs, and socioeconomic conditions have significant effects on the spread of WNV caused by mosquitoes and animal hosts in the study area, through the interpretation and analysis of landscape metrics, correlation, factor, and regression. Remote sensing and GIS techniques were used to derive information of landscape pattern and LSTs in the study area. WNV dissemination is an ongoing problem, and the results of this analysis can contribute to urban planning and public health management and protection in the study area and other areas with similar character.

Methodology

Study area

Cook County, Illinois has been chosen to implement the study of the effects of landscape pattern, land surface temperature, and socioeconomic conditions on WNV transmission. The city of Chicago (41°53′ N, 87°38′ W), the seat of Cook County, Illinois, is the nation's third largest city and the largest city in Illinois in population. It is located at the southwestern tip of Lake Michigan with the elevation of 182 m. The city proper extends over 588 km^2. It has a population of about 2.9 million according to the US Census 2000. The climate in Chicago is continental with frequently changing temperatures ranging from relatively warm in summer time to relatively cold in winter time. Its annual average temperature is 49.8°F, and the average temperature in January is only 23.0°F and 74.7°F in July. The average annual precipitation is 35.8 in. and about 1.9 in. in January and 3.7 in. in July. The lake area experiences heavy snowfall in the winter due to moisture from Lake Michigan.

Serving as the primary connection between the east coast cities and western part of the nation, the city is the financial and cultural center in the central east of the nation. It has advanced industry, transportation, and infrastructure diversity and is famous for its agricultural commodities. The population has kept increasing in recent decades. Urbanization has affected the habitats and thermal environment in the Greater Chicago area. The region also contains a variety of types of natural communities that include some of the best remaining remnants of Midwest wilderness, such as open oak woodland. Figure 1 shows the geographic location of the study area.

This study focused on the total cumulative numbers of West Nile virus infection in mosquitoes, birds, horses, and other mosquitoes/animal hosts of WNV in the study area. The Cook County is the second largest county of the country by population with more than 5 million in 2004. The county has 138 municipalities (cities, villages, and incorporated towns) with an area of 1,635 $miles^2$, and 42.16% of it is water (most of it in Lake Michigan) according to the statistic results of US Census Bureau. The City of Chicago is the largest municipality in the county with 24% area percentage. Any other municipalities are around the City of Chicago and spread to the north, west, and south of the county. It has the third largest public health system in the country.

The Illinois Department of Public Health maintains a disease surveillance system to monitor insects and animals that can potentially carry WNV: mosquitoes, dead crows, robins, blue jays, and horses. Mosquitoes can either carry the virus or get it by feeding on infected birds. While many mosquito abatement districts and other agencies collect and test mosquitoes, the department asks the public for help with the collection of dead birds in their backyards. The surveillance system then requests experts in different fields, such as infectious disease physicians and infection control practitioners, to test for and report suspect or confirmed cases of various diseases that can be caused by WNV. The Cook County Public Health Department has published WNV surveillance data based on county level for years 2001–2007 (URL: http://www.idph.state.il.us/envhealth/wnv.htm). The natural features of the county provide good environmental conditions for mosquitoes, the main vector of WNV. These features include wetlands, forest, prairies, and aquatic systems throughout the county.

Remote sensing data preparation

This study acquired information of landscape patterns and land surface temperatures by processing four Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images purchased from the National Aeronautics and Space Administration (NASA). ASTER imagery carries 15-m resolution in visible bands and 90-m

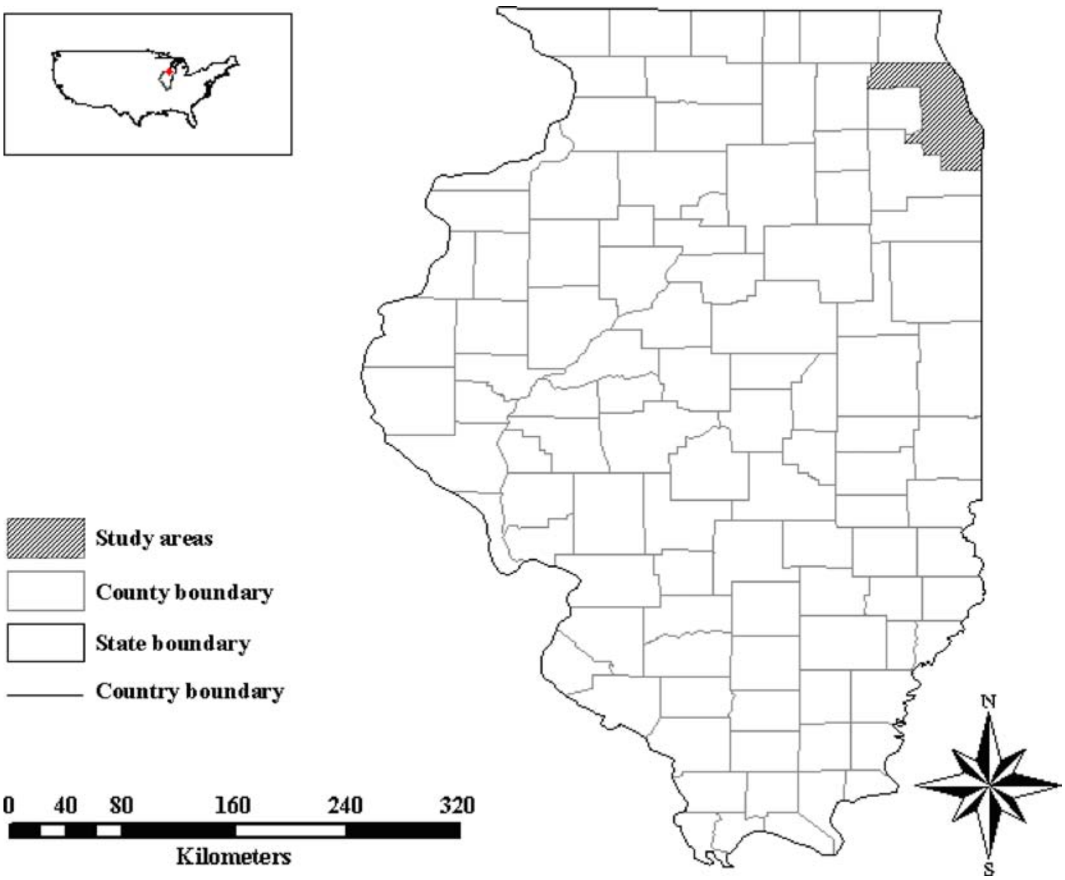


Fig. 1 Geographical location of the study area

resolution in thermal band, which provide great opportunity to identify landscape patterns and retrieve land surface temperatures. All the images were acquired in the same day (September 10, 2004) except the one covering the southwestern corner of the county (acquired on 10/12/2003) because no image could be found to cover the corner with the same acquisition date. The WNV study was based on the data collection in 3 months (August, September, and October in 2004). The landscape patterns are believed to not experience significant changes during the leave-on season (Liu and Weng 2008). So it is still significant to use image from September 10, 2004 to indicate the environmental factor for the whole season. By using ERDAS Imagine software, these images were geocorrected and given the projection to NAD27 north Zone 16, Clarke 1866, with the reference of Illinois Digital Raster Graphics data.

Urban areas usually include a large population and huge consumptions of resource, which provide various channels of WNV infection, like old tires, tin cans, buckets, drums, bottles or any water-holding containers. Forests and grassy areas appear to provide relatively ideal environments for birds to live (Komar 2003; Rainham 2005). Areas around water have relatively higher moisture and contribute to the gathering of some mosquitoes (Komar 2003). In this study, six LULC types, urban, forest, grass, agriculture, water, and barren land were separated from remote sensing imagery. Wetlands were classified into water since no detailed references were collected as reference in the image classification. One hundred and twenty clusters were produced during the unsupervised classification process and labeled to specific LULC types with the reference of 2005 Chicago orthography data. The overall accuracy of classification reached 85.67%. Figure 2 lists the LULC maps for the study area. Known from the figure, urban areas and grass were the dominant LULC types in the county.

Land surface kinetic temperature data were purchased from NASA with 90-m resolutions through a free entry. The temperature–emissivity separation algorithm was applied to compute land surface kinetic temperatures (ASTER products description 2005). According to the product description, the absolute accuracy of the kinetic temperature data is accurate within 1.5 K and relative accuracy 0.3 K. In Fig. 3, the whole study area was classified into six temperature zones by the use of natural break method (Smith 1986). The red colors in central and north part of the county indicate that those areas possessed relatively high temperature than their surrounding areas. Areas in blue color were the places with lowest temperatures.

Landscape metrics deviation

Five landscape-level landscape metrics, Landscape Shape Index, perimeter–area fractal dimension, mean perimeter–area ratio, Contagion Index, and Shannon's Diversity Index were derived from LULC map for municipalities having

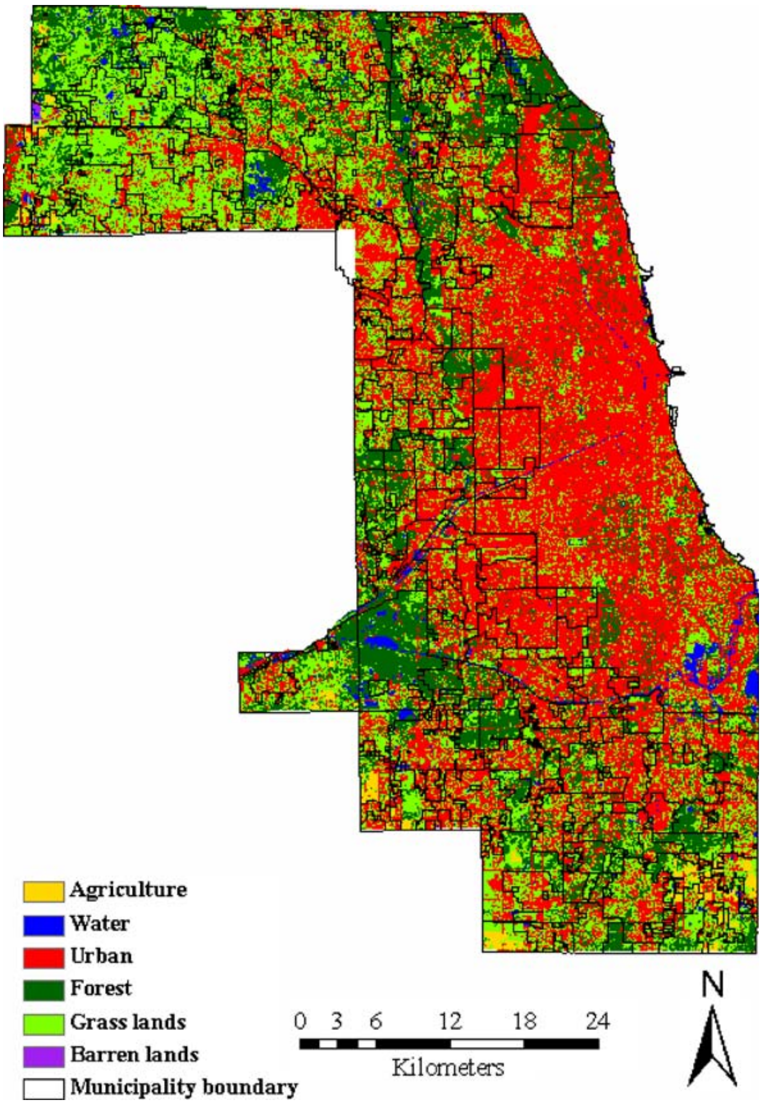


Fig. 2 LULC map for Cook County in fall 2004

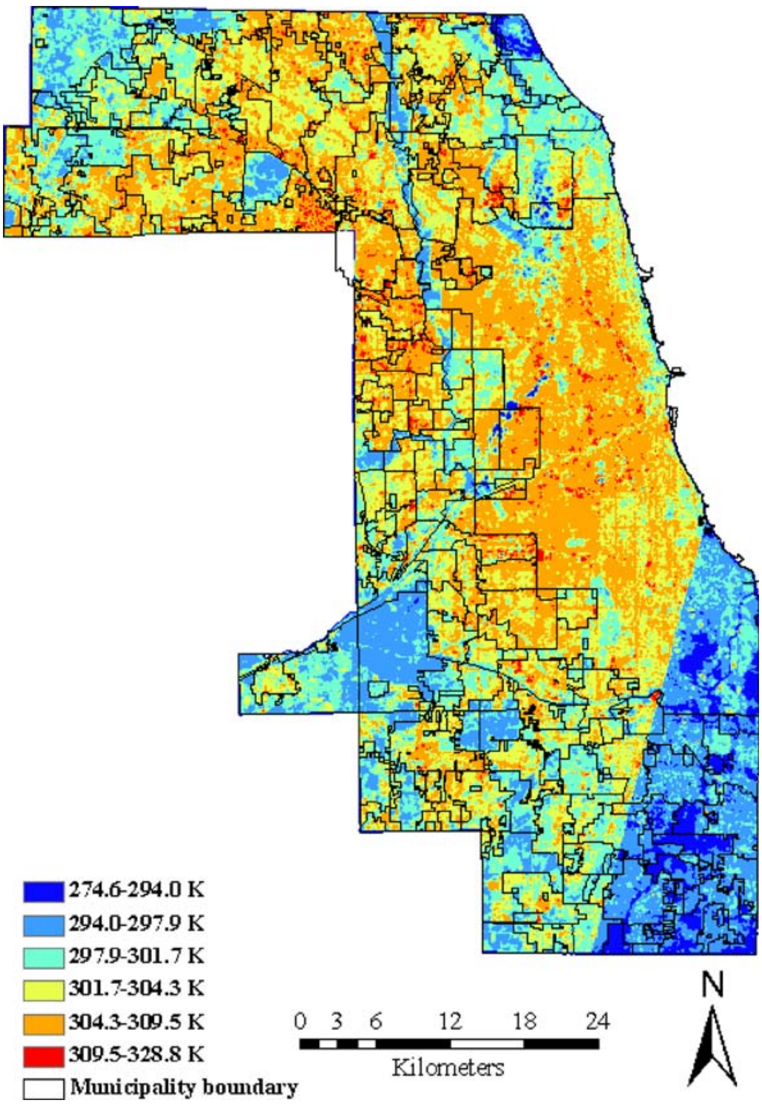


Fig. 3 LST map for Cook County in fall, 2004. A distinct different color composition was observed in the southeast corner of the county because the ASTER data covering that portion of the county were acquired on a different day and year from the other images

mosquito/animal host positive reports, with the use of ArcGIS software and FRAGSTATS, a popular software program for computing a wide variety of landscape metrics for categorical map patterns (McGarigal and Marks 1995). Since urban, forested, grassy, and water areas were the main components in the study area and are believed to show significant effects to the spread of WNV (Komar 2003; Rainham 2005), their landscape patterns in individual municipalities were examined by the derivation of five class-level landscape metrics, percentage of landscape, area of landscape, patch density, perimeter–area fractal dimension, and patch cohesion index. A total of 25 variables related to landscape pattern of the study area were produced and would be used as inputs in further statistic analysis.

LST and socioeconomic conditions

Absolute numbers of mosquito/animal host positive cases include the cumulative totals of West Nile virus infection in mosquitoes, birds, and horses. The absolute numbers in fall (August, September, and October) from year 2000 to 2006 were collected from the Cook County Public Health Department as a unit of municipality. The municipalities without positive records of WNV were excluded from the study. No human case was included in the study limited by the availability of WNV data. Only the WNV data for year 2004 were used in the statistic analysis. The rest of the data were used to show the changes of spatial distributions of WNV in 7 years (years 2000–2006). Remote sensing data, municipal boundaries, and socioeconomic data needed to be integrated since they had different formats and spatial resolutions. Six socioeconomic conditions for municipalities having mosquito/animal host positive reports were obtained from US Census 2000: total human population, area, perimeter, population above 65 years old, total house income, and income below poverty line. The mean temperatures of municipalities having mosquito/animal host (mosquitoes, birds, horses, and other mosquitoes/animal hosts) positive reports of WNV were calculated by the integration of remote sensing data and a municipal boundary shape file with the help of ArcGIS software. The statistic features of temperature, maximum, minimum, standard deviation, and range for urban area, forest, grass, and water were also computed for those municipalities. A total of 17 temperature-related variables were prepared for further statistic analysis of the spread of WNV. As a result, 48 variables were created for the study. Table 1 lists all 48 variables and their abbreviations.

Model development

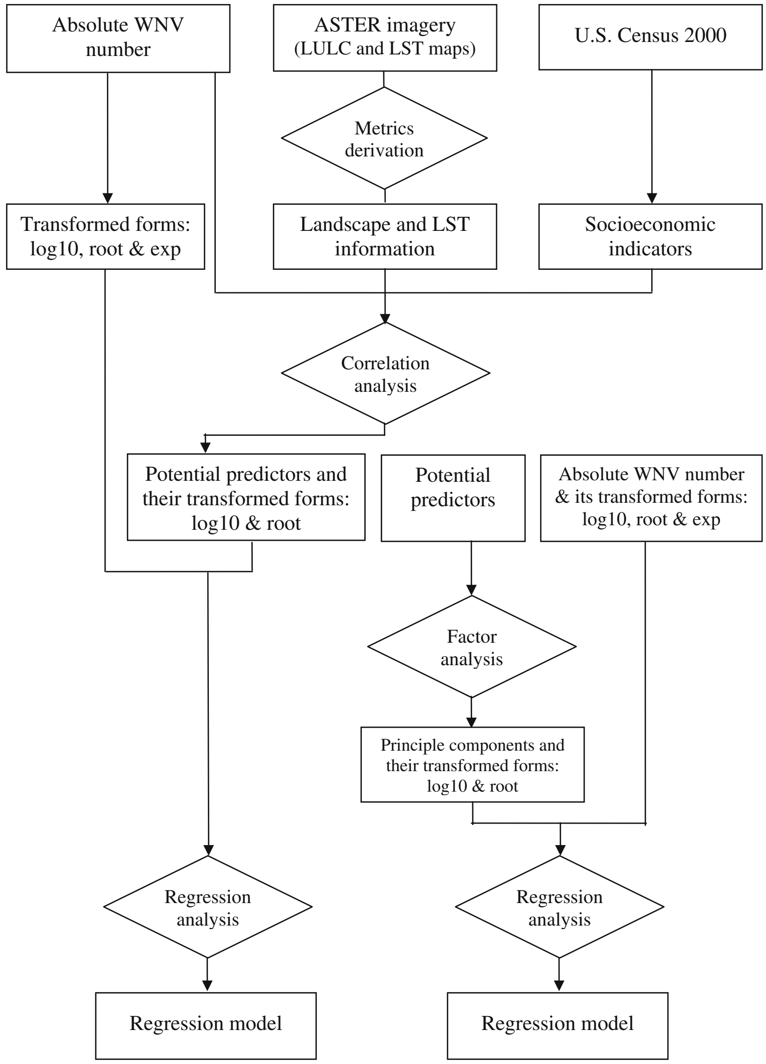
Figure 4 is the flowchart of the research development. In order to further identify the effects of landscape pattern, LST, and socioeconomic conditions on the spread of WNV, WNV record in fall (August to October), 2004 was then selected for statistical analysis since this season and year matched the acquisition date of remote sensing data available in this study. According to the reports of the Cook County Public Health Department, forty-nine municipalities were reported to have mosquito/animal host positive results of WNV in fall, 2004. To determine which environmental and socioeconomic variables possessed

Table 1 Variables related to landscape pattern, LST, and socioeconomic aspects

Variables	Abbreviations
Landscape shape index*	LSI
Mean perimeter–area ratio	Par_MN
Fractal dimension	FRD
Contagion index	COI
Shannon's diversity index	SDI
Urban area*	Urb_Are
Urban percentage	Urb_Per
Urban patch density	Urb_Den
Urban fractal dimension	Urb_Fra
Urban cohesion	Urb_Coh
Forest area	For_Are
Forest percentage	For_Per
Forest patch density	For_Den
Forest fractal dimension	For_Fra
Forest cohesion	For_Coh
Grass area*	Gra_Are
Grass percentage	Gra_Per
Grass patch density	Gra_Den
Grass fractal dimension	Gra_Fra
Grass cohesion	Gra_Coh
Water area*	Wat_Are
Water percentage	Wat_Per
Water patch density	Wat_Den
Water fractal dimension	Wat_Fra
Water cohesion	Wat_Coh
Mean temperature	Tem_MN
Maximum urban temperature*	UT_Max
Minimum urban temperature*	UT_Min
Standard deviation of urban temperature*	UT_SD
Range of urban temperature*	UT_RG
Maximum forest temperature	FT_Max
Minimum forest temperature	FT_Min
Standard deviation of forest temperature	FT_SD
Range of forest temperature	FT_RG
Maximum grass temperature*	GT_Max
Minimum grass temperature	GT_Min
Standard grass of urban temperature*	GT_SD
Range of grass temperature*	GT_RG
Maximum water temperature	WT_Max
Minimum water temperature	WT_Min
Standard deviation of water temperature*	WT_SD
Range of water temperature*	WT_RG
Total population*	Pop
Total area*	Are
Population above 65 years old*	Abo_65
Perimeter	Per
Total income*	Inc
Family below poverty line*	Bel_Pov

Variables with * were the variables selected as potential predictors in the factor analysis and regression analysis

Fig. 4 Flowchart of the study



significant relationships with the spread of WNV, these 49 municipalities were input as cases in the correlation and regression analysis based on 48 variables listed in Table 1. S-Plus software was used in the statistics analysis. Only variables that showed significant correlation to the absolute number of mosquito/animal host WNV cases were used for further statistical analysis. To develop significant regression models for the study, all potential predictors selected after correlation analysis were transformed into natural logarithm and square root. Variables outside of three standard deviations were removed as outliers. The t statistic was applied to identify the significance of a potential predictor.

Although significant results would be produced based on the variables selected from correlation analysis, the question, how landscape pattern, LST, and socioeconomic conditions affect WNV dissemination still needs to be answered. Factor analysis was then used in this study to further examine how the underlying dimensions of those variables affected the WNV dissemination. The underlying dimensions produced in factor analysis can explain most of the variability among the observations. Principal component analysis was chosen in this study as one of the factor extraction methods. Bartlett's test and Kaiser–Olkin (KMO) values were chosen to examine the suitability of all variables. These data can be acceptable for factor analysis only when KMO is greater than 0.5 and the significant level of Bartlett's test was less than 0.1. The variables were further validated based on communality of variables. Small values indicate that variables do not fit well with the factor analysis method used and needs to be withdrawn from the analysis.

A step-wise regression analysis was applied to examine the relationships between the spread of WNV and landscape pattern, LST, and socioeconomic conditions. A series of regression equations were developed to model the effects of landscape pattern, LST, and socioeconomic conditions on WNV dissemination separately. The dependent variable was the absolute number of mosquito/animal host positive reports of WNV in municipalities. Independent variables were chosen which were highly correlated with mosquito/animal host positive cases. The natural logarithm and square root forms of these variables were also used as inputs in the regression analysis for possible better result. The t statistic was used to identify the relative importance of potential predictors in the regression analysis. Variables with t statistic above 2 or less than -2 were considered to be important predictors in the regression result.

Result

Spatial distributions of WNV infections

The total insect/animal (mosquitoes, birds, horses, and other hosts) positive reports of WNV slightly decreased from 2002 to 2003 and heavily increased after 2003 for the whole county. For the City of Chicago, the number of the mosquito/animal host positive reports reached a maximum in 2002; even the mosquito/animal host positive cases for the whole county kept increasing after year 2003. More mosquito/animal host positive cases in fall 2001 were reported in north and south part of the county and the City of Chicago compared to those in year 2002. The WNV cases were spread to the central west of the county since year 2002. More cases were found in the northern part of the county in fall of years 2004 and 2005. In fall, 2006, the cases decreased in the northern part of the county, but an obviously increase of WNV infections in the southern part of the county in fall 2006 indicates that the county apparently experienced much serious situation over that area in 2006. Since no references show how comprehensively and correctly the mosquito/animal host positive cases were reported in each year, no direct conclusion could be reached only based on these records. But the WNV maps show significant changes through years 2001 to 2006. The WNV dissemination map for fall 2004 was recorded in Fig. 5 as an example.

Correlation analysis results

All 48 variables in Table 1 were used to examine their relationships with the absolute number of mosquito/animal host positive reports of WNV in the study area. According to the Pearson correlation coefficients (Table 2), some variables showed a stronger relationship with the absolute WNV number than some other variables, like human population, area, total house income, and urban area and areas of water and grass in municipalities. Some variables showed relatively lower correlation with the WNV number, like standard deviation and range of water temperature in municipalities (WT_SD, WT_RG). Population (Pop) showed very strong relationship with landscape aggregation (landscape shape index (LSI)) and area-related variables, such as urban, grass, and water areas. Variables that showed poor Pearson correlation coefficients were dropped from the statistic analysis. Totally, 18 variables were selected as potential predictors in the regression modeling. They were labeled with asterisks in Table 1.

Factor analysis results

In the factor analysis, all 18 variables were initially inputted for processing. KMO (0.863) and Bartlett's test (significant level 0.000) indicated that the variables inputted were suitable for factor analysis. No variable was dropped according to

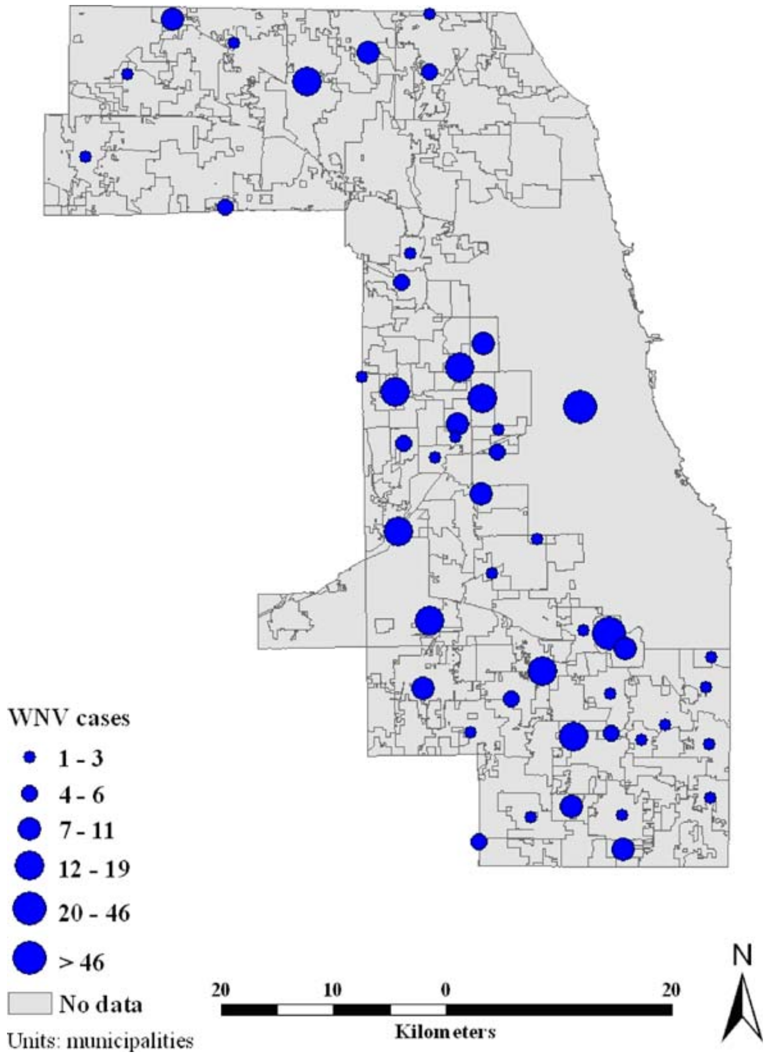


Fig. 5 Absolute number of mosquito/animal host positive reports of WNV in Cook County in fall, 2004. Municipal map was chosen as base map

the calculation of communality. Variamax rotation method was chosen in the processing. Four components were extracted from factor analysis with a rule that the minimum eigenvalue should not be less than 1. As a result, component 1 explained 61.252% of the total variance, component 2 explained 15.988%, component 3 accounted for 8.660%, and component 4 accounted for 7.020%. Together, the first four components explained more than 90% of the variance.

Factor loading shows the relationship between variable and factor. Factor loadings of 0.71 or higher are believed excellent (Comrey and Lee 1992), factor loadings of 0.63 are very good, loadings of 0.55 are good, loadings of 0.45 are fair, and factor loadings of 0.32 are poor. Table 3 records rotated factor loading matrix in this study. Component 1 has very high values of positive loadings (greater than 0.75) on nine variables, total population, area (Are), population above 65 years old (Abo_65), landscape shape index, urban area (Urb_Are), grass area (Gra_Are), water area (WT_Are), total income (Inc), and family below poverty line (Bel_Pov). Apparently, component 1 is associated with landscape pattern and socioeconomic conditions. The higher the score in component 1, the more mosquito/animal host positive reports of WNV would be expected. Component 2 has high positive loadings (greater than 0.6) on four variables, maximum temperatures of

Table 2 Pearson correlation coefficients for dependent variable and representatives of independent variables

		WNV number	Pop	Are	LSI	WT_Are	Urb_Are	GT_RG	UT_Max	WT_SD
WNV number	Pearson correlation	1	0.649**	0.658**	0.546**	0.631**	0.636**	0.418**	0.383**	0.348*
	Sig. (2-tailed)		0.000	0.000	0.000	0.000	0.000	0.003	0.007	0.014
	N	49	49	49	49	49	49	49	49	49
Pop	Pearson correlation	0.649**	1	0.992**	0.821**	0.991**	0.999**	0.228	0.371**	0.290*
	Sig. (2-tailed)	0.000		0.000	0.000	0.000	0.000	0.115	0.009	0.043
	N	49	49	49	49	49	49	49	49	49
Are	Pearson correlation	0.658**	0.992**	1	0.856**	0.991**	0.992**	0.259	0.403**	0.328*
	Sig. (2-tailed)	0.000	0.000		0.000	0.000	0.000	0.072	0.004	0.022
	N	49	49	49	49	49	49	49	49	49
LSI	Pearson correlation	0.546**	0.821**	0.856**	1	0.822**	0.828**	0.383**	0.493**	0.445**
	Sig. (2-tailed)	0.000	0.000	0.000		0.000	0.000	0.007	0.000	0.001
	N	49	49	49	49	49	49	49	49	49
WT_Are	Pearson correlation	0.631**	0.991**	0.991**	0.822**	1	0.990**	0.207	0.349*	0.293*
	Sig. (2-tailed)	0.000	0.000	0.000	0.000		0.000	0.153	0.014	0.041
	N	49	49	49	49	49	49	49	49	49
Urb_Are	Pearson correlation	0.636**	0.999**	0.992**	0.828**	0.990**	1	0.232	0.380**	0.300*
	Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000		0.108	0.007	0.037
	N	49	49	49	49	49	49	49	49	49
Bel_Pov	Pearson correlation	0.641**	0.999**	0.988**	0.804**	0.990**	0.998**	0.213	0.358*	0.276
	Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	0.142	0.012	0.055
	N	49	49	49	49	49	49	49	49	49
GT_RG	Pearson correlation	0.418**	0.228	0.259	0.383**	0.207	0.232	1	0.643**	0.153
	Sig. (2-tailed)	0.003	0.115	0.072	0.007	0.153	0.108		0.000	0.292
	N	49	49	49	49	49	49	49	49	49
UT_Max	Pearson correlation	0.383**	0.371**	0.403**	0.493**	0.349*	0.380**	0.643**	1	0.252
	Sig. (2-tailed)	0.007	0.009	0.004	0.000	0.014	0.007	0.000		0.081
	N	49	49	49	49	49	49	49	49	49
WT_SD	Pearson correlation	0.348*	0.290*	0.328*	0.445**	0.293*	0.300*	0.153	0.252	1
	Sig. (2-tailed)	0.014	0.043	0.022	0.001	0.041	0.037	0.292	0.081	
	N	49	49	49	49	49	49	49	49	49

*$p = 0.05$, correlation is significant (two-tailed)
**$p = 0.01$, correlation is significant (two-tailed)

Table 3 Rotated factor loading matrix

Indicators	Component 1	Component 2	Component 3	Component 4
Pop	0.97	0.09	0.18	0.12
Are	0.96	0.13	0.17	0.18
Abo_65	0.96	0.10	0.17	0.14
LSI	0.78	0.32	0.04	0.39
Urb_Are	0.97	0.11	0.17	0.13
Gra_Are	0.88	0.24	0.12	0.26
WT_Are	0.96	0.07	0.18	0.15
Inc	0.97	0.09	0.18	0.13
Bel_Pov	0.97	0.08	0.18	0.10
GT_Max	0.03	0.95	0.03	0.13
GT_RG	0.05	0.74	0.58	0.06
UT_Max	0.28	0.91	0.05	0.08
UT_RG	0.54	0.62	0.46	0.19
UT_Min	−0.56	0.15	−0.72	−0.23
UT_SD	0.43	0.06	0.74	0.17
GT_SD	0.02	0.45	0.84	−0.13
WT_SD	0.15	0.14	0.01	0.91
WT_RG	0.38	0.08	0.14	0.85
Initial eigenvalues	11.03	2.88	1.56	1.26
% of variance	61.25	15.99	8.66	7.02
Cumulative %				

See Table 1 for the explanations of abbreviations

urban and grass areas, and temperature ranges of urban and grass areas. Component 2 is clearly related to thermal conditions of urban and grass areas in maximum temperature. The higher the score of component 2, the more mosquito/animal host positive reports of WNV would be expected. Component 3 shows high positive factor loadings (greater than 0.72) on standard deviations of urban and grass temperatures (UT_SD and GT_SD). It shows negative factor loading on minimum temperature of urban area (UT_Min) and thus is related to thermal conditions of urban and grass areas in standard deviation. The higher the score in component, the lower minim4um temperature of urban area would be expected.

The City of Chicago had a relatively high factor score in component 1 but had median factor scores in the rest of the components. It indicates that landscape and socioeconomic conditions of Chicago significantly contributed to the formation of component 1, and the thermal conditions of urban, grass, and water areas in the city did not show the same effect as those of landscape and socioeconomic conditions. It is noted that there were some municipalities marked in grey because there was no WNV record reported in those municipalities in fall, 2004.

Regression analysis results

Stepwise regression analysis was produced to identify relationships between dependent variable (the absolute number of reported WNV cases) and 18 independent variables and their transformed forms. The results were summarized in Table 4. Model 1 had all 18 variables as model inputs, and four out of 18 remained after regression analysis (population above 65 years old, urban area, the maximum grass temperature, and standard deviation of urban surface temperature). Model 2 used natural logarithm of all the inputs in model 1 as potential predictors, and two variables remained after analysis (natural logarithms of the minimum urban surface temperature and the maximum grass temperature). Model 3 had square roots of all the inputs in model 1, and four predictors remained after regression analysis (square roots of population above 65 years old, urban area, urban surface temperature, and the maximum grass temperature). Model 4 used all 18 initial variables and their transformation forms, natural logarithm, and square root as inputs. There were three variables that remained after analysis: square roots of population above 65 years old, urban area, and grass temperature.

Table 4 Potential predictors, *t* statistics, and *R* square (R^2) values for regression models (independent variable: absolute WNV number)

Model	Potential predictor	Unstandardized coefficient		*t* statistic	R^2
		B	Std. error		
1	(Constant)	−25.030	7.007	−3.572	0.75
	Abo_65	0.002	0.000	6.356	
	Urb_Are	−0.012	0.002	−5.972	
	GT_Max	0.480	0.132	3.635	
	UT_SD	5.077	2.158	2.353	
2	(Constant)	−19.651	31.501	−0.624	0.50
	UTI_Log	−52.690	9.118	−5.779	
	GTM_Log	59.350	17.795	3.335	
3	(Constant)	−56.178	15.624	−3.596	0.69
	Abo65_Sqr	0.227	0.040	5.693	
	UA_Sqr	−0.453	0.109	−4.139	
	UTS_Sqr	21.148	6.756	3.130	
	GTM_Sqr	4.477	1.957	2.288	
4	(Constant)	7.905	8.168	0.968	0.75
	Abo65_Sqr	0.398	0.054	7.408	
	UA_Sqr	−0.732	0.125	−5.852	
	GT_Max	0.673	0.157	4.302	

For the rest of the variables, see Table 1 for the explanations of abbreviations

UT_SD standard deviation of urban temperature, *GT_Max* maximum grass temperature, *UTI_Log* natural logarithm of the minimum urban surface temperature, *GTM_Log* natural logarithm of the maximum grass temperature, *Abo65_Sqr* square root of population above 65 years old, *UTS_Sqr* square root of standard deviation of urban surface temperature, *GTM_Sqr* square root of the maximum grass temperature, *UA_Sqr* square root of urban area

According to Table 4, transformation itself did not increase the R^2 value but decreased the value instead.

Model 1 appeared to be the optimal models in Table 4. In the model, the combination of four variables effectively predicted the absolute WNV number with an R^2 value of 0.75. The residual of WNV number for City of Chicago was underestimated. Negative residuals occurred more in the northern and southern parts of the county. This indicates that those municipalities were overestimated by the model.

Once four principal components or factors were decided in factor analysis, regression analysis can be applied to relate absolute WNV number to the aspects of landscape pattern, thermal, and socioeconomic conditions. A regression model was developed based on each principal component. All the variables in each of the four components were input as potential predictors in the regression analysis (see Table 2 for details) and were next used to predict the WNV number. Table 5 shows the dependent variable, potential predictors, and R^2 values of regression models based on four principle components. All the models in Table 5 had the same independent variable (the absolute number of WNV). Their R^2 values kept decreasing when the dependent variables changed from principal components to their square root forms and then to their natural logarithm forms. This indicates that these transforms did not significantly increase the effectiveness of prediction but decreased it instead. Principle component 1 was apparently related to the highest R^2 value in the group compared to any other principal component. Components 2 and 3 did not show the same high R^2 values as that of component 1. Component 4 possessed the smallest R^2 value. It indicates that landscape and socioeconomic conditions better explained the WNV dissemination than thermal indicators (maximum temperatures of urban and grass areas, standard deviation of urban and grass temperatures, and water thermal conditions).

This study found that urban and grass areas apparently showed a close relationship with the spread of WNV caused by insects and animals. This finding supports the knowledge that mosquitoes,

Table 5 Regression model groups and their R^2 values

Model groups	Independent variables	Potential predictors											
		PC1	$\sqrt{PC1}$	Log10 (PC1)	PC2	$\sqrt{PC2}$	Log10 (PC2)	PC3	$\sqrt{PC3}$	Log10 (PC3)	PC4	$\sqrt{PC4}$	Log10 (PC4)
I	Absolute WNV number	0.67	0.62	0.46	0.44	0.37	0.27	0.41	0.36	0.37	0.16	0.11	0.02
II	Square root of absolute WNV number	0.50	0.46	0.34	0.38	0.32	0.25	0.26	0.28	0.26	0.16	0.12	0.11
III	Natural logarithm of WNV number	0.33	0.31	0.24	0.30	0.26	0.21	0.16	0.16	0.16	0.12	0.11	0.11

PC1, *PC2*, *PC3*, and *PC4* principle components 1, 2, 3 and 4; *Log10 (PC1)*, *Log10 (PC2)*, *Log10 (PC3)*, and *Log10 (PC4)* natural logarithms of principle components 1, 2, 3, and 4; $\sqrt{PC1}$, $\sqrt{PC2}$, $\sqrt{PC3}$, and $\sqrt{PC4}$ square root of principle components 1, 2, 3, and 4

the vector of WNV dissemination, prefer to stay in habitats with high organic content and fine moisture, such as old tires and storm water catch basins in the residential area. This finding also indicates that the composition of different LULC types in the study area may affect the WNV dissemination more than a single factor can do. It may be related to the growing population and urbanization in recent years in the study area. For example, more discarded tires could be exposed in the back yards, and more pipes would be added to existing sewer systems.

Discussions and conclusions

This study demonstrates that ASTER imagery could be used to examine the spread of WNV by combining various remote sensing and GIS related variables and thermal and socioeconomic information. However, it is still a challenging work to use remote sensing and GIS techniques to study the spread of WNV due to some factors: the quality of remote sensing data, their acquisition time and methods used to process them, the complexity of WNV dissemination, and the integrity and reliability of the records of infections (mosquito/animal host positive reports). Remote sensing data with higher resolutions may provide more detailed information on landscape patterns. The accuracy of LSTs retrieved from remote sensing data can be affected by sensor resolution and algorithm chosen. Specific acquisition time of remote sensing data restricts the study to specific periods and decreases the possibility of combining WNV reports in different seasons, unless remote sensing data acquired at different seasons would be available. More specific land use and land cover categories (e.g., commercial areas and residential communities) can be identified by using different classification methods. This study found out that urban and grass areas apparently showed a close relationship with the spread of WNV caused by *Culex* species and hosts. This indicates that the composition of different LULC types may affect the WNV dissemination more than a single factor. More detailed records of WNV cases, like physical addresses of cases, are expected to improve the accuracy of analysis.

Based on the results identified in the last section, we concluded that:

1. WNV infections caused by insects and animals were spread throughout the whole Cook County since 2001. The size of urban area, urban and grass temperatures, and population above 65 years old were the most important factors for the spread of WNV in Cook County. The landscape aggregation level and areas of three LULC types, urban area, grass, and water, showed high correlations with the spread of WNV caused by insects and animals no matter how high or low their patch densities were, how complicated their spatial configurations may be, and how high or low their spatial connectivity were.
2. Socioeconomic conditions, population, total area, population above 65 years old, total house income, and income below poverty line also showed strong relationships with the spread of WNV caused by insects and animals in Cook County. The combination of these variables predicted the WNV number with acceptable R^2 value.
3. Thermal conditions like maximum temperatures and standard deviations of urban and grass areas were also related to the spread of WNV caused by insects/animals. Thermal conditions of water (standard deviation and range) showed less but still considerable correlation to the spread of WNV compared to those of urban and grass areas.

This study further proves the capability of remote sensing and GIS techniques in the study of public health. Some findings in this study could contribute to urban planning and public health management and protection in the studied area and other areas with similar character:

1. Epidemic disease control can benefit from remote sensing and GIS techniques. Remotely sensed imagery could be used to derive environmental factors that are believed to be closely related to any specific epidemic diseases, such as land surface temperature and water fractal dimension. The techniques used in remote sensing and GIS can produce significant inputs for the further analysis such as geographical statistics (Ruiz et al. 2004, 2007).
2. The aggregation levels and sizes of urban areas, grass, and water need to be controlled so as to decrease the possibilities of disease dissemination. In this study, the aggregations and sizes of urban area, grass, and water show close relationship to the spread of WNV caused by insects and animals. In order to decrease the spread of WNV caused by insects and animals in the Cook County, possible measures include developing more green vegetation zones with small sizes in the urban area, so as to decrease the urban area and its aggregation level, decreasing the sizes of existing grasslands, ponds, and lakes, controlling the sizes of those features, and limiting their aggregation levels in the future urban planning.
3. It is necessary to pay extra attention to older people and low-income families in the Cook County. According to the conclusion, socioeconomic factors, population above 65 years old, total house income, and income below poverty line showed strong relationship with the spread of WNV caused by insects and animals in Cook County. Possible measures are to help low-income families maintain a clean living environment and to increase the medical assistants for population above 65 years old.
4. Attention is also needed in temperature control of the Cook County. High land surface temperatures of urban area, grass, and water may contribute to the WNV dissemination. Possible solutions can include decrease energy transfer and control pollution: decreasing the use of vehicles, avoiding urban sprawl, planting more green vegetation, and so on.

Further research is expected to improve the examination of how landscape pattern, thermal condition, and socioeconomic indicators affect the spread of WNV: (1) to introduce soil moisture and housing age information to the study; moisture index can be derived from remote sensing data (Houser et al. 1998); housing age can be collected from US Census 2000; (2) to further analyze the spread of WNV at a larger (more localized) scale;

the WNV records used in this study was for municipalities since those are the only ones available; better results may be achieved if more detailed reports (based on specific geographic locations or addresses) were available; and (3) to obtain multitemporal remote sensing data and WNV information so as to develop models for different seasons and to compare with the results in this study.

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