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Geographic incidence of human West Nile virus in northern Virginia, USA, in relation to incidence in birds and variations in urban environment

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ABSTRACT

Previous studies have analyzed the number and location of bird infections with human incidence of West Nile virus (WNV) as well as the effects of environmental and socioeconomic factors on WNV propagation. However, such associations require more quantitative analyses. This study is intended to quantitatively analyze the relationship in eight counties/independent cities in the northern Virginia, based on an integrated analysis of spatially explicit information on precipitation, land cover, infrastructure, and demographic data using Geographical Information Systems, remote sensing, and statistics. Results show that bird infections in years 2002–2003 were closely associated with low to medium level of impervious surface with certain percentage of canopy and precipitation. Environmental and socioeconomic factors such as percentages of impervious surface, canopy, senior population (65 and older), old houses, bird risk areas, and low-income population were important indicators of human WNV risk in 2002. Limited impervious surface with some canopy provides suitable habitats for WNV transmission, where bird-feeding mosquitoes can forage for blood meals from nesting/roosting birds. Certain socioeconomic conditions such as old houses were linked with human infections by providing favorable environmental conditions, i.e., mature trees with abundant canopy and settled storm sewer systems. It should be noted that the current results may be biased toward urban environments, where dead birds were more likely found, and because the sampling efforts for the bird mortality were rather based on local residents' reports than a designed random sampling method. This geospatial study contributes toward better targeting of WNV prevention within the study area. It also provides an example of how geospatial methods and variables may be used in understanding the ecology of human WNV risk for other areas.

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1. Introduction

West Nile virus (WNV) is a mosquito-borne flavivirus that causes approximately one out of every 256 infected persons to develop serious neurological symptoms (Busch et al., 2006). WNV symptoms may be complicated by hypertension, immuno-suppressing conditions, and cardiovascular disease (Murray et al., 2009). Its dissemination can vary seasonally and in response to the characteristics of landscape patterns and environmental and socioeconomic conditions in the urban settings (Bertolotti et al., 2008; Brown et al., 2008; Liu et al., 2008). According to the guidelines for surveillance, prevention and control issued by CDC in 2003, many states adopted bird surveillance as a sensitive means of detecting WNV activity since 2000 in an effort to monitor the spread of activity and target preventive measures. Previous studies have analyzed the number and location of bird infections with human incidence of West Nile virus (Johnson et al., 2006). Other studies have analyzed the effects of environmental and socioeconomic factors on WNV propagation (Cooke et al., 2006; Ozdenerol et al., 2008). Some bird species (e.g., crow and perhaps blue jays) may be linked to the apparent incidence of WNV in the urban environment and to the sylvatic cycle of WNV (Chevalier et al., 2009). However, such associations require a more quantitative analysis than the previous studies. This study examines the quantitative relationship between corvid infection and the geographic distribution of human WNV cases, based on an integrated analysis of Geographic Information Systems (GIS), remote sensing, and statistical analysis on spatially explicit information on precipitation, land cover, infrastructure, and demographic data. This type of geospatial study contributes toward a better targeting of WNV prevention and prediction of human WNV risk.

2. Materials and methods

2.1. Study area

Northern Virginia was selected because it had greater numbers of human WNV cases than any other locality in the state of Virginia, with

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18 human cases in 2002 and 8 in 2003. The 2002 and 2003 seasons were selected for study as the total number of human WNV cases reported in any subsequent year did not exceed six when this study was conducted. The area includes three counties (Arlington, Fairfax, and Prince William) and five independent cities (Alexandria, Fairfax, Falls Church, Manassas, and Manassas Park). It is considered to be part of the Washington D.C. metropolitan area with a combined human population of approximately 1.7 million in 2003, about 23% of the state's total human population (U.S. Census Bureau). The most important mosquitoes acting as primary WNV vectors in Virginia are *Culex pipiens* and *Culex restuans* (Virginia Department of Health). Breeding habitats for these species include water in artificial containers, underground storm sewer systems, stagnant ditches, puddles and marshes. Among the bird species that were tested for WNV in northern Virginia during the study period, 89.6% were crows, and 7.8% were blue jays (Virginia Department of Health).

2.2. Data collection and processing

Tabular records of laboratory-confirmed dead bird and human WNV infections in 2002–2003 were provided by the Virginia Department of Health, including collection/onset date, species name, and latitude/longitude. To identify the temporal change of WNV outbreaks in 2002 and 2003, the absolute numbers of WNV incidences (both human and bird) were plotted with epidemiological weeks as units for both years. According to the description of Pan American Health Organization Epidemiological Bulletin, the epidemiological week is used for epidemiological studies as a compromise between using daily or monthly surveillance records since daily records incur a lot of frequently varying results and monthly data omit too many details to be useful. The study assumed that none of the infected humans traveled outside of the study area, where they have been bitten by infected mosquitoes before or during the period of study.

Some studies have shown that land cover types such as vegetated urban areas correlated well with WNV dissemination (Ruiz et al., 2004; Cooke et al., 2006; Liu et al., 2008). As birds usually roost or nest in trees, and most infected birds were found in public or residential areas, our interest focused on assessing the influence of levels of urbanization and canopy density on WNV transmission. Two environmental variables, percent of impervious surface (i.e., pavement) and percent of tree canopy cover were derived from National Land Cover Database (NLCD) 2001. When integrated together, two conditions can be an effective indicator for the favorability of habitats for both birds and mosquitoes. With the use of remote sensing and GIS technologies, we classified % impervious surface into five classes corresponding to the ranges of 0–20%, 21–40%, 41–60%, 61–80%, and 81–100%, and four classes for percent of canopy density, 0–20%, 21–40%, 41–60%, and 61–100%. We then created 20 impervious surface-canopy density combinations, such as 0–20% impervious surface with 20–40% canopy density. These combinations were used as input factors in the discriminant analysis of WNV infections.

Significantly high precipitation showed a positive relationship to WNV incidence in humans and mosquitoes (Epstein and Defilippo, 2001; Landesman et al., 2007). Daily precipitations for both years were collected from NOAA. To better interpolate the precipitation we chose 34 existing weather stations located inside and immediately surrounding the study area. We calculated the mean weekly precipitation for individual census block groups by spatially interpolating the precipitation with the Inverse Distance Weighting algorithm. A total of 21 variables (20 impervious surface-canopy density combinations and precipitation) were prepared for discriminant analysis on bird infection. In addition, house density was obtained from U.S. Census Bureau 2000 as an indicator of residential density.

2.3. Discriminant analysis and distance measure

Discriminant analysis allows examination of the differences between two or more groups of targets on the basis of some particular characteristics (Lachenbruch, 1975). All the input variables were normalized based on the number of laboratory-confirmed dead bird WNV infections. Stepwise discriminant analysis (Wilks' lambda method) was developed to distinguish census block groups with and without WNV bird infection. To be consistent, we performed analyses for epidemiological weeks 26–37 only in each year. The variables retained after the analysis were used as inputs in the distance measure.

Mahalanobis distance is an index based on correlation between variables by which different conditions can be analyzed (Mahalanobis, 1936). We used Mahalanobis distance to identify risk areas for WNV in birds. We assumed that the census block groups with confirmed bird infections had different environmental characteristics from those without confirmed dead bird infections. Shorter distances indicate areas with higher risk of WNV in birds, and longer distance associates with lower risk.

To identify the possible association between human and bird infections, another discriminant analysis was performed based on census tracts (with and without human cases), in which all the input variables were normalized based on the number of human cases. The analysis focused on the census tracts in Alexandria, Arlington, Fairfax (both county and city), and Falls Church, because this area possessed all but one of the human cases reported in 2002–2003 (the excluded one was found in Prince William County). The mean Mahalanobis distance for bird incidence in each census tract was computed and used as input in human analysis. The assumption was that a human infection in a certain census tract was the consequence of viral transmission from an infected bird/mosquito locally. Other variables were the combinations of impervious surface and tree density and socio-economic variables based on U.S. Census Bureau 2000, including population density, percent of population with age $\geq$65, median household income, percent of population with income below poverty line, percent of houses with age $\geq$50, and housing density. Mahalanobis distance was calculated to assess the risk areas of human infection based on the variables retained after the second discriminant analysis.

3. Results

3.1. WNV surveillance data

Fig. 2 shows the absolute numbers of laboratory-confirmed WNV infections for dead birds and humans in individual epidemiological weeks for 2002 and 2003. In 2002, the first WNV infected bird was collected in epidemiological week 21 (late May). Collections of WNV-infected dead birds peaked in week 30 (late July), and declined to low numbers after week 32 (early August). Human case onsets started much later, from week 33 (mid-August) to week 39 (late September). In 2003, the first infected bird was found in week 26 (late June), about 4 weeks later than that in 2002. Collections of WNV-infected dead birds reached a peak in week 32 (early August) and declined to low numbers after week 33 (mid-August). The onset of the first human case occurred in week 34 (mid-August) in 2003 and the last case had an onset in week 39 (late September). Overall, the year 2002 had more reported bird and human WNV infections than 2003, and the peak in bird infections preceded the first human infections by a few weeks in both years.

3.2. Results of discriminant analysis and distance measure

Table 1 shows the results of discriminant analysis on lab-confirmed bird and human infections. According to the table, some

Fig. 1. Geographic location of the study area.

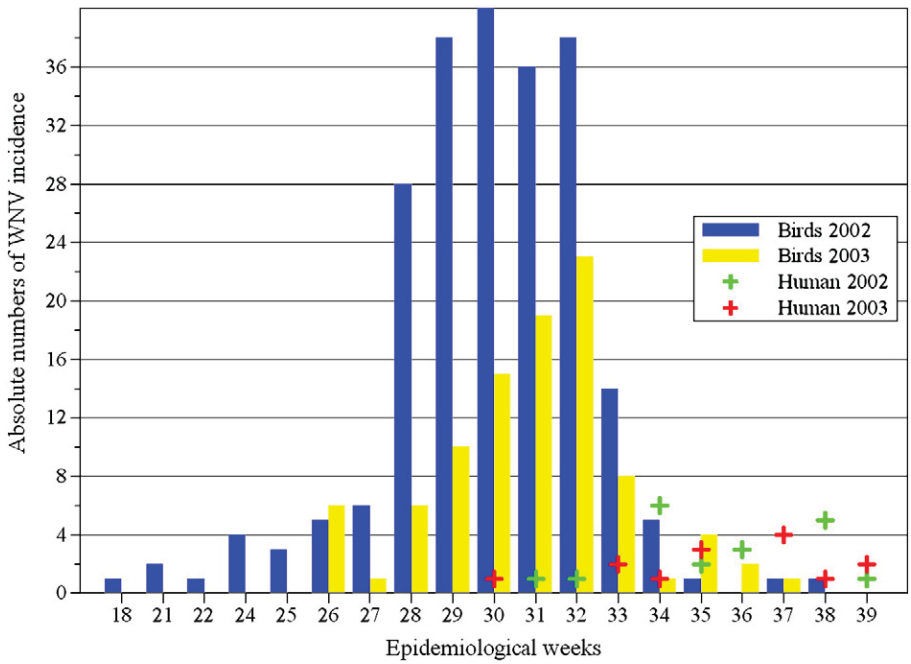

Fig. 2. Absolute numbers of laboratory-confirmed WNV infections in birds and humans by epidemiological week in 2002 and 2003.

Table 1
Function coefficients, weighted mean values, eigenvalues, and Wilks' lambda values of discriminant analysis for census block groups or tracts with and without WNV-infected dead birds or human in the epidemiological weeks 26–37, 2002 and 2003 (all the retained variables are significant at the level of 0.001). Positive values of the function coefficients indicate that the variable positively contributes to the WNV dissemination, with negative values implying inverse contribution to the spread of WNV. The magnitudes of the coefficients indicate the importance of the variables, whether positive or negative, to the dissemination. No significant result was obtained based on human analysis in 2003 due to limited number of cases reported in the year.

Year	Independent variable	Function coefficient	Weighted mean for census block groups (bird) or tracts (human)		Eigenvalue, Wilks' lambda
			With bird incidence	Without bird incidence	
2002 (bird)	Mean weekly precipitation in 2002	0.652	1.651 m	1.335 m	0.216, 0.823
	0–20% impe. with 21–40% canopy	0.511	10.350%	6.958%	
	21–40% impe. with 21–40% canopy	0.371	5.219%	3.584%	
	0–20% impe. with 41–60% canopy	0.364	8.778%	6.483%	
	0–20% impe. with 0–20% canopy	0.208	21.903%	18.301%	
2003 (bird)	0–20% impe. with 0–20% canopy	0.572	33.086%	17.835%	0.254, 0.798
	0–20% impe. with 61–100% canopy	0.464	36.295%	18.443%	
	Mean weekly precipitation in 2003	0.179	2.219 m	1.961 m	
	41–60% impe. with 0–20% canopy	−0.134	12.215%	15.397%	
	House density	−0.134	809.012	1276.293	
	61–80% impe. with 0–20% canopy	−0.123	6.535%	9.519%	
2002 (human)	0–20% impe. with 20–40% canopy	0.711	15.795%	7.360%	0.481, 0.675
	Percentage of population with age ≥ 65	0.656	19.307%	9.375%	
	21–40% impe. with 21–40% canopy	0.522	7.494%	3.677%	
	0–20% impe. with 0–20% canopy	0.231	25.203%	18.393%	
	Percentage of houses with age ≥ 50	0.200	24.858%	14.015%	
	Mean Mahalanobis distance based on bird analysis in 2002	−0.285	2.320	4.272	
	Percentage of population with income below poverty line	−0.060	5.588%	6.824%	

Note: "impe." means impervious surface.

environmental variables were found positively correlated to bird infection, i.e., mean weekly precipitation and low to moderate percentage (0–20% and 21–40%) of impervious surface with 21–40% canopy density in the weeks of 26–37, 2002. The result for 2003 suggested a similar association between the physical environment and WNV dissemination as in 2002, i.e., 0–20% impervious surface with 0–20% and 61–100% canopy densities was positively linked with bird infection (Table 1). However the association with the level of precipitation was lower in 2003 although it still showed a positive relationship with WNV infection in birds. The combination of 41–80% impervious surface with 0–20% canopy was negatively associated with the spread of WNV in birds.

Fig. 3(a) and (b) shows the results of Mahalanobis distance analysis based on the environmental variables listed in the table as an indication of bird risk distribution. The bird risk areas in red were mainly distributed in the northern and eastern parts of the study area in 2002 (Fig. 3a). In 2003, relatively few infected birds were found in the urban areas with low-intensity single-family houses and 21–40% canopy (Fig. 3b). The majority of infected birds found in 2003 were in less urbanized southern and western parts in places that had 0–20% impervious surface and either 0–20% canopy or 61–100% canopy.

The result of discriminant analysis on human infection (Table 1) indicates that a combination of environmental and socioeconomic factors contributed to the spread of WNV in humans, and that distance to bird risk areas also played a role in human infection in 2002. However no significant result was obtained based on human analysis in 2003 due to limited number of cases reported in the year. Based on the function coefficients shown in the table, census tracts with high human WNV risk in 2002 tended to comprise less impervious surface (i.e., 0–20%) with a moderate percentage of canopy (i.e., 21–40%), higher proportions of senior population (65 or older) and old houses, and had shorter distance to identified bird risk areas and less percentage of population with income below poverty line.

The negative correlation (coefficient = −0.285) between human incidence and the Mahalanobis distance for bird infections (Table 1), conforms to a previous finding of the association between human and bird infections (Cooke et al., 2006). The percentage of population below the poverty line was also found to be negatively associated with WNV dissemination. This finding contradicts a study in Memphis, TN in which the factor showed a positive correlation with the propagation of human WNV. This difference may be due to considerably higher standards of living, and possibly different types of housing occupied by low income populations in northern Virginia than in Memphis, TN. In northern Virginia census tracts with less affluent populations were less likely to have big yards and abundant tree canopy for birds.

As for the environmental conditions (impervious surface and canopy), human WNV cases were detected in census tracts with averages of 22.8% impervious surface (range: 8.9–49.2%) and 28.5% canopy coverage (range: 3.2–54.3%) in 2002, and 29.7% impervious surface (range: 16.9–49.2%) and 18.55% canopy (range: 3.2–35.0%) in 2003. The examination of impervious surface and canopy levels indicates that human cases were mostly observed in the low to medium-density residential areas with some amount of canopy. Fig. 4(a) and (b) presents the risk areas of WNV human infection based on the Mahalanobis distance (Fig. 4a) and its relation to population density (Fig. 4b). Risk areas were mainly concentrated in Fairfax and Arlington Counties and the cities of Fairfax and Falls Church where population density was low to moderate.

4. Discussion and conclusions

This study identified the associations between human and dead bird cases and urban environment settings in northern Virginia. The current results show that environmental and socioeconomic factors such as low to medium percentage of impervious surface with certain canopy, senior population (65 and older), old houses, bird risk areas, and low-income population may be used to indicate human WNV risk in the northern Virginia in 2002. The results indicate that the urban environments of northern Virginia where people are at higher risk of WNV infection can be identified using remote sensing data and analysis of environmental variables like percentages of impervious surface and canopy, census data proportions of senior citizens and the age of house, and bird risk areas. As 2002 was the first year in which high levels of WNV were observed in northern Virginia, high levels of crow mortality in that year (LaDeau et al., 2007) and possible increased antibody immunity in other bird species (Ringia et al., 2004; Brinton, 2009) may have reduced and changed the geographic pattern

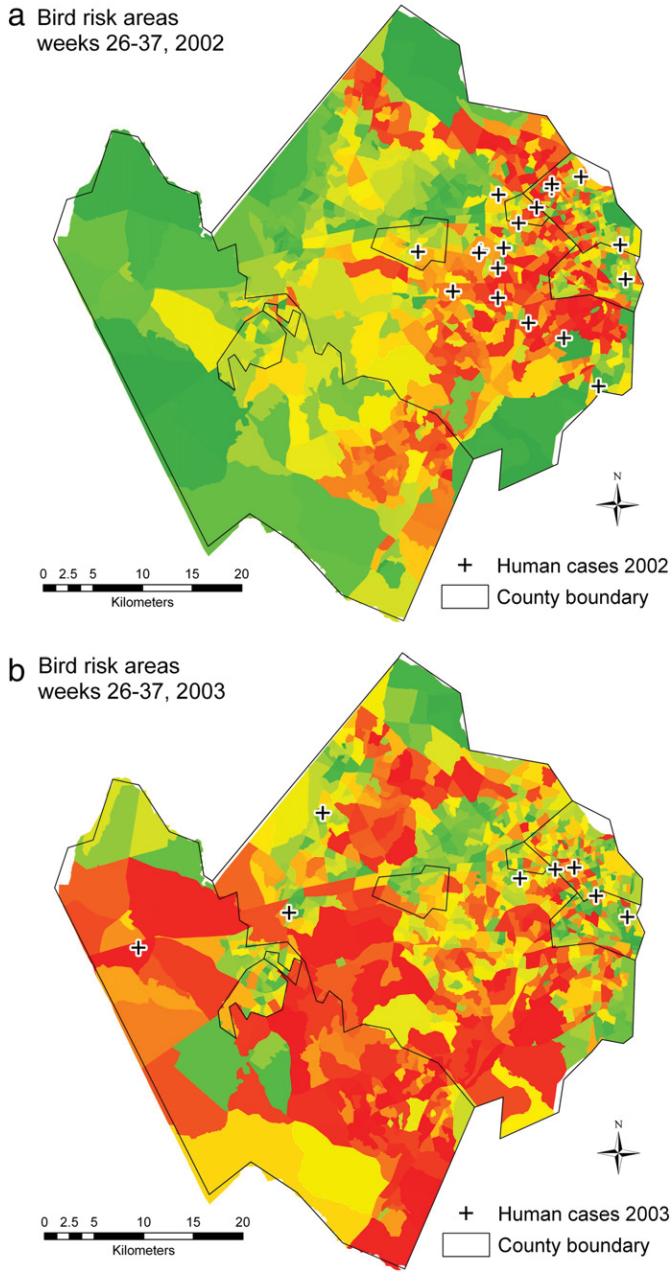

Fig. 3. Risk areas for bird infections in weeks 26–37 in years 2002 (panel a) and 2003 (panel b). In each map, red color associates with shorter Mahalanobis distance indicating higher risk; green color corresponds to longer distance, which implies lower risk areas. Units: census block groups.

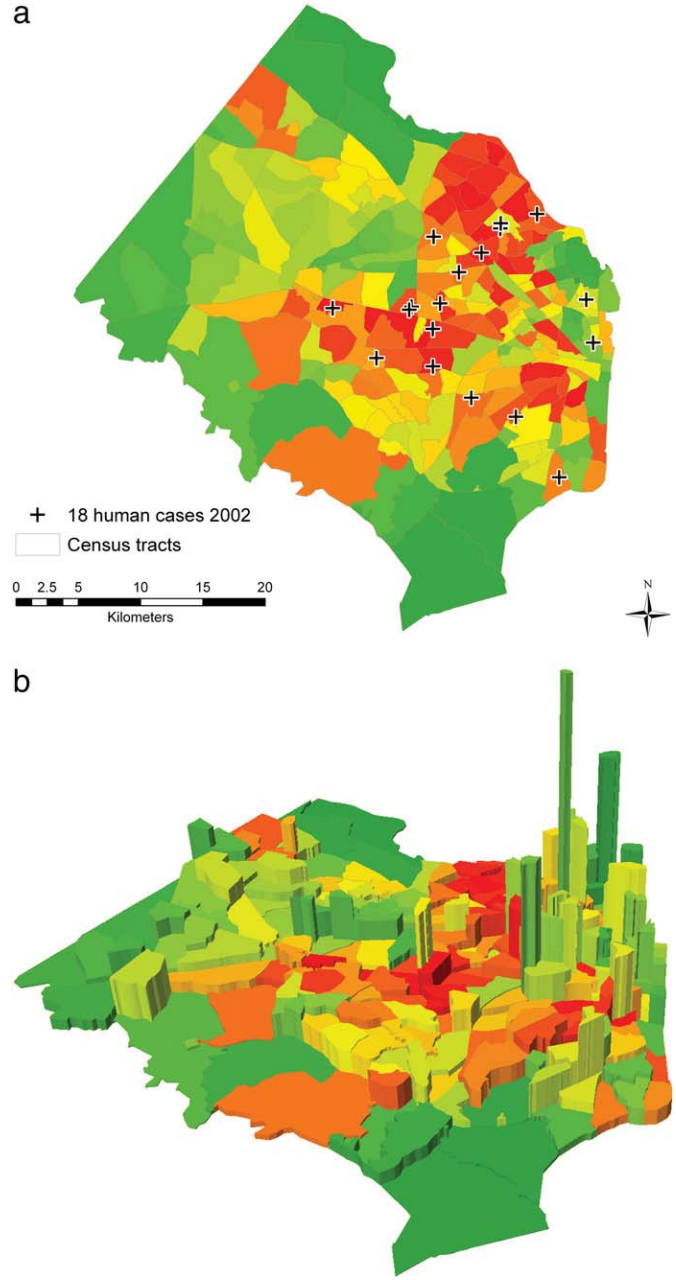

Fig. 4. Risk area for human WNV disease in the study area (excluding Manassas, Manassas Park, and Prince William) in 2002. Units: census tracts. In both panels a and b, red color is associated with higher risk of WNV in humans and green color corresponds to lower risk areas. In panel b higher bar indicates greater population density, and vice versa. Prince William County and the cities of Manassas and Manassas Park were left out of this map (see Fig. 1 for its location) as only one human case occurred there in Prince William County. No statistically significant result was returned in year 2003 due to its fairly small number of human cases.

of transmission in 2003. However, the types of high risk urban environments identified in 2002 should be targeted for future WNV monitoring and prevention activities in the local area. More specifically, local vector control agencies should pay more attention to those identified risk areas in devising the spatial range of mosquito control and allocating supplies and equipment. The public can be better informed about WNV and the importance of reporting dead bird bodies, and thus more complete bird surveillance data can be recorded and analyzed to improve the modeling.

Based on the definitions of NLCD 2001 given by the Multi-Resolution Land Characteristics (MRLC) Consortium, 0–40% impervious surface with 21–40% canopy is usually related to developed open green spaces (i.e., parks) and low-intensity single-family houses. These greener environmental settings appeared to provide suitable habitats for WNV transmission in the early summer of 2002. Developed open green spaces and low-intensity residential areas with tree canopy provided necessary foraging and nesting habitat for birds such as crows, robins or cardinals that may play important roles in the bird–mosquito–bird transmission/amplification cycle for WNV (Chevalier et al., 2009). Tree canopy and other vegetation also provide an environment where bird-feeding mosquitoes can forage for blood meals from nesting/roosting birds.

In the factors contributing to bird infection based on discriminant analysis (Table 1), rainfall brings moisture needed for mosquitoes to

breed (Landesman et al., 2007), thereby potentially encouraging the multiplication of WNV in 2002. Rainfall levels were higher in the summer and fall of 2003 than in the same seasons of 2002. Heavier rainfall may impact the number of available mosquito breeding habitats in underground storm sewer systems by constantly flushing them out in most urban areas while maintaining puddles as suitable breeding habitats in more rural areas to the south and west. The more humid environment may also lead to a drop in air and land surface temperatures which may have slowed the extrinsic rate of WNV incubation in *C. pipiens* mosquitoes (Dohm et al., 2002) and thus delayed virus transmission.

According to the definitions of land cover types given by MRLC Consortium, 41–80% impervious surface is commonly observed in medium to high-density residential and commercial lands where medium-intensity houses, apartment buildings, commercial districts or industrial areas predominate. Birds have difficulty finding nesting places in those areas with low canopy density, which interferes with the spread of the virus. Housing density also was negatively associated with WNV dissemination. When the housing density is high, it is less likely that birds have places to nest and less likely the virus can be disseminated in the neighborhoods.

For the factors contributing to human infection as shown in Table 1, senior residents were found to be at higher risk of severe illness and even death from WNV (Weiss et al., 2001). The relationship between house age and human WNV case incidence might be explained by the neighborhood characteristics where old houses predominate, the condition of older underground storm sewer systems in these older neighborhoods, and the behavior of people living in the older houses. Older free standing houses are usually located in the neighborhoods with mature trees and abundant canopy. Underground pipes in older storm sewer systems were more likely to have settled, leaving depressions that hold underground pools of water. Stagnant water sitting in these older drainage systems could have provided more breeding habitats for *C. pipiens* mosquitoes than in newer neighborhoods, contributing to more transmission of WNV in older neighborhoods. Older houses may be less likely to have air conditioning, thus potentially leading to people leaving windows open and spending more time outside, increasing their risk of exposure to mosquitoes. Although this analysis of human infection analysis was developed based on limited number of human cases with the assumption that a human infection in a certain census tract was the consequence of viral transmission from an infected bird/mosquito locally, the methodology developed in this study provides potentials for similar studies based on larger samples in other areas. Overall, the methodology can help to better understand the WNV ecology. Our method assumed that WNV dissemination across space and time was possible by effectively transmitted mosquito vectors across land with suitable environmental, climate, and socioeconomic conditions. By assessing and monitoring the favorable environmental and socioeconomic settings for virus spread in an urban area, neighborhoods can be identified for intensified mosquito control efforts such as aerial spraying of mosquito adulticide. Public awareness of WNV infection can be improved by providing residents with more specific information on the mechanism of viral transmission.

A limitation of this study relates to the method of data collection. Firstly, a neighborhood's education level or socioeconomic status may influence levels of citizen awareness of programs for WNV surveillance in dead birds, and the reporting of dead birds to authorities. Secondly, persons may be more likely to feel directly affected by the presence of a dead bird on their own property, and report it, as opposed to a dead bird observed in a parking lot or beside a road. Thirdly, dead birds are more likely to be detected and collected in moderate density residential areas because yards are not so large that a dead bird would go un-noticed. Although most of the infected birds were collected in residential areas, there were some collections of dead crows in the commercial areas with high impervious surface and low percentage of canopy. The occurrence of crows in commercial areas may be due to their foraging activities at restaurant dumpsters. Dead birds in rural, sparsely populated areas may not be reported to the local health department for testing. Bias might exist in dead bird submissions based on collection efforts and disinterest by the public as the number of collected dead birds varied between years. We made a potentially biased assumption that none of the infected humans traveled elsewhere where they might be bitten by infected mosquitoes, before or during the period of study. Despite the potential limitation of this assumption, we kept all the human records in the analysis in order to obtain more statistically significant results based on the human cases.

Some other factors may have contributed to the variations of WNV dissemination between the 2 years. Meteorological conditions (drought and winter conditions) in the 2 years were different. Virginia had a very warm 2001–2002 winter season, which may have enabled higher levels of early WNV transmission activity by the overwintering *C. pipiens* mosquito population in 2002. In the same year, the state experienced a multi-month drought in spring and summer. Droughts have been associated with urban outbreaks of WNV in the continental U.S., Eastern Europe and the Middle East (Epstein and Defilippo, 2001). The cooler springtime weather combined with a possible increased WNV immunity in the local adult bird population and a diminished crow population may explain why the first infected bird was not detected until June in 2003. The change in importance of precipitation over the 2 years indicates that this issue requires future investigation in future studies.

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