Original Investigation

The 2012 West Nile Encephalitis Epidemic in Dallas, Texas

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IMPORTANCE After progressive declines over recent years, in 2012 West Nile virus epidemics resurged nationwide, with the greatest number of cases centered in Dallas County, Texas.

OBJECTIVE To analyze the epidemiologic, meteorologic, and geospatial features of the 2012 Dallas West Nile virus epidemic to guide future prevention efforts.

DESIGN, SETTING, AND PATIENTS Public health surveillance of Dallas County, an area of 2257 km^2 and population of 2.4 million. Surveillance data included numbers of residents diagnosed with West Nile virus infection between May 30, 2012, and December 3, 2012; mosquito trap results; weather data; and syndromic surveillance from area emergency departments.

MAIN OUTCOMES AND MEASURES Incidence and age-adjusted incidence rates of West Nile neuroinvasive disease (WNND), daily prevalence of emergency department visits for asthma and skin rash, and *Culex quinquefasciatus* species-specific vector index (an estimate of the average number of West Nile virus–infected mosquitoes per trap-night).

RESULTS The investigation identified 173 cases of WNND, 225 of West Nile fever, 17 West Nile virus–positive blood donors, and 19 deaths in 2012. The incidence rate for WNND was 7.30 per 100 000 residents in 2012, compared with 2.91 per 100 000 in 2006, the largest previous Dallas County outbreak. An unusually rapid and early escalation of large numbers of human cases closely followed increasing infection trends in mosquitoes. The *Cx quinquefasciatus* species-specific vector index predicted the onset of symptoms among WNND cases 1 to 2 weeks later (count regression β = 2.97 [95% CI, 2.34 to 3.60]; $P < .001$). Although initially widely distributed, WNND cases soon clustered in neighborhoods with high housing density in the north central area of the county, reflecting higher vector indices and following geospatial patterns of West Nile virus in prior years. During the 11 years since West Nile virus was first identified in Dallas, the log-transformed annual prevalence of WNND was inversely associated with the number of days with low temperatures below 28°F (−2.2°C) in December through February (β = −0.29 [95% CI, −0.36 to −0.21]; $P < .001$). Aerial insecticide spraying was not associated with increases in emergency department visits for respiratory symptoms (β = −4.03 [95% CI, −13.76 to 5.70]; $P = .42$) or skin rash (β = −1.00 [95% CI, −6.92 to 4.92]; $P = .74$).

CONCLUSIONS AND RELEVANCE Large West Nile virus epidemics in Dallas County begin early after unusually warm winters, revisit similar geographical distributions, and are strongly predicted by the mosquito vector index. Consideration of weather patterns and historical geographical hot spots and acting on the vector index may help prevent West Nile virus–associated illness.

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After declining over the prior 5 years, mosquito-borne West Nile virus infection resurged in 2012 throughout the United States, most substantially in Dallas County, Texas.[1] Dallas has been a known focus of mosquito-borne encephalitis since 1966, when a large epidemic of St Louis encephalitis (SLE) occurred there, necessitating aerial spraying of insecticide for control.[2] A serologic survey of residents living in a flood-prone area of Dallas demonstrated evidence of recurrent arboviral infection before the 1966 SLE epidemic.[3] With the introduction of West Nile virus into New York City in 1999 and its subsequent spread across the country,[4] West Nile virus appears to have displaced SLE virus. Dallas recognized its initial cases of West Nile virus encephalitis in 2002 and its first sizeable outbreak in 2006, followed by 5 years of low West Nile virus activity.

In the 2012 nationwide West Nile virus resurgence, Dallas County experienced the most West Nile virus infections of any US urban area,[4] requiring intensified ground and aerial spraying of insecticides. The large size of the 2012 Dallas epidemic, combined with 11 years of prospective West Nile virus human and mosquito surveillance data, provided an opportunity to address urgent questions about the causes and the most effective surveillance and control measures for minimizing future outbreaks.

Methods

Human West Nile Virus Infection Surveillance

With the first West Nile virus–positive mosquito trap in May 2012, health advisories were sent to area physicians recommending diagnostic West Nile virus testing of patients with symptoms suggestive of West Nile neuroinvasive disease (WNND). All West Nile virus–positive laboratory test results (IgM, IgG, or polymerase chain reaction assay from serum or cerebrospinal fluid) were electronically reported to Dallas County Health and Human Services (DCHHS) through NEDSS (National Electronic Disease Surveillance System).[5] Health department staff reviewed NEDSS reports of patients with any West Nile virus–positive test result, and those meeting laboratory case criteria were classified as WNND or West Nile fever cases by the national case definition[6] from medical records (including initial history and physical examination, progress and consult notes as needed, and discharge summaries) and patient or family interviews. All available West Nile virus IgM–positive specimens (n = 145) sent to the state laboratory were confirmed. Reports of West Nile viremic blood donors were received from blood collection agencies. The University of Texas Southwestern institutional review board determined that this public health response was not human subjects research and did not require the board's review or oversight.

Mosquito West Nile Virus Infection Surveillance

Mosquitoes were trapped with gravid traps through the existing DCHHS and 11 municipal West Nile virus surveillance programs from May 1 through December 19, 2012. Pools of 50 or fewer female *Culex quinquefasciatus* mosquitoes, the primary local West Nile virus vector, were screened for the virus by viral culture or reverse transcription-polymerase chain reaction assay. The weekly species-specific vector index for *Cx quinquefasciatus* mosquitoes was calculated as the product of mosquito abundance (average number of mosquitoes collected per trap-night) and West Nile virus mosquito infection rate from a bias-corrected maximum likelihood estimation divided by 1000 (eAppendix [Supplement]).[7-10] The vector index estimates the average number of West Nile virus–infected mosquitoes per trap-night.

The power of the vector index to predict the subsequent onset of WNND cases was tested with negative binomial count regression performed with the Countreg procedure of SAS version 9.3 (SAS Institute Inc). The incidence of WNND cases by week of symptom onset was regressed on the weekly vector index with lags of 1 to 4 weeks, yielding 95% CIs calculated from quasi-maximum likelihood standard errors robust to heteroscedasticity in the time-series data. Autocorrelation was assessed with the Box-Pierce Q test.

Geospatial Analysis

Human West Nile virus cases and West Nile virus–positive mosquito traps were mapped using ArcGIS version 10.0 (Esri). Census tract incidence rates of WNND cases were adjusted to the age distribution of Dallas County and mapped.[11] "Hot spot analysis" of age-adjusted WNND incidence rates, performed with the Spatial Analyst extension (version 10) to ArcGIS, used *z* scores of the Getis-Ord Gi* statistic to estimate strength of clustering of high-risk census tracts.[12,13]

Weather Pattern Analysis

The association of the annual incidence of West Nile virus human infections (log transformed) with local weather data[14] from 2002 to 2012 was assessed with stepwise multiple regression analysis, using the SAS Regression procedure. Autocorrelation was assessed with the SAS Arima procedure.

Syndromic Surveillance Analysis

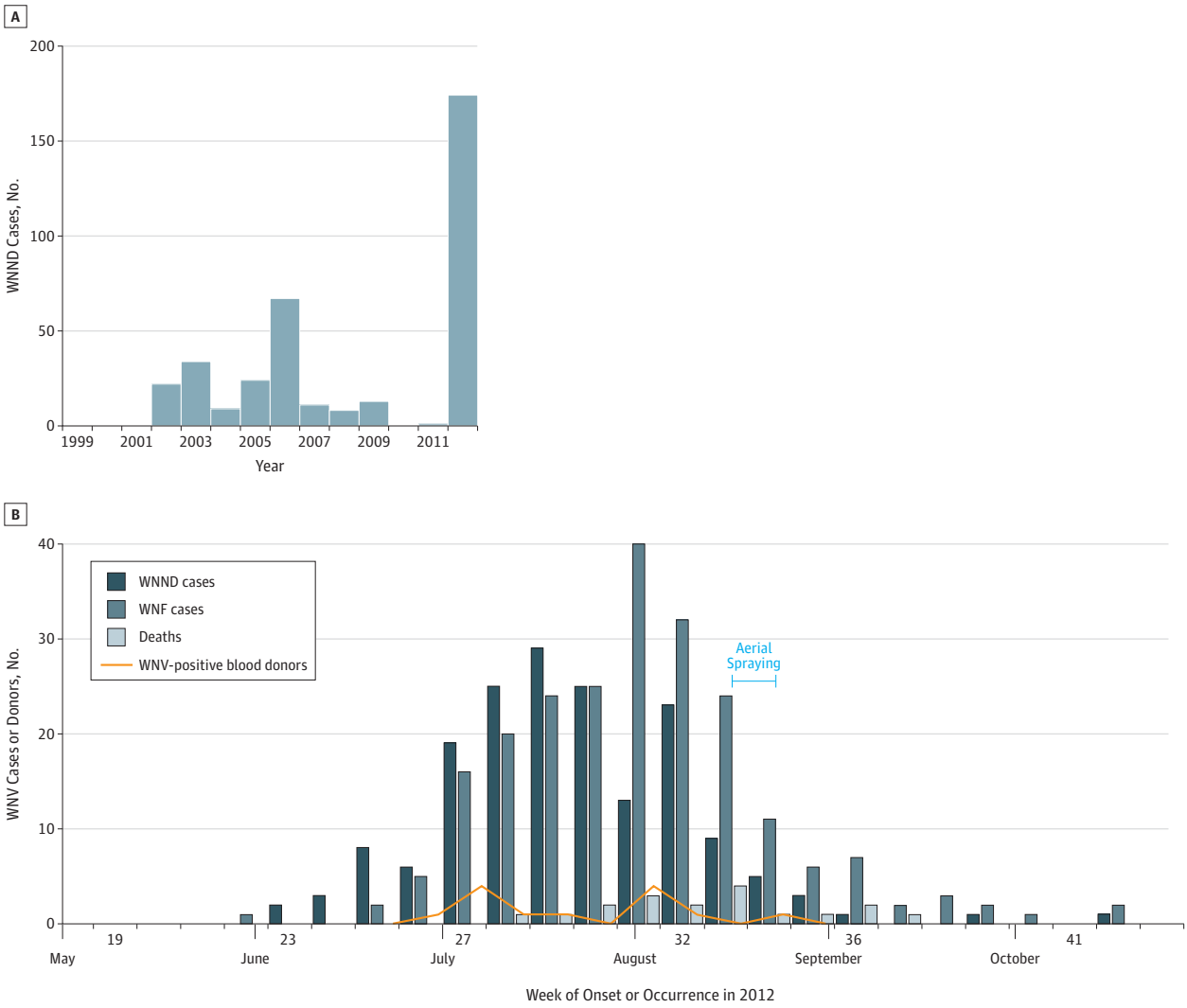
The incidence of emergency department visits for chief concern of skin rash or respiratory distress (asthma, shortness of breath, and lower respiratory tract symptoms) was abstracted from the Electronic Surveillance System for the Early Notification of Community-based Epidemics (ESSENCE) from July 1, 2012, to August 31, 2012.[15,16] Time-series event study analysis with the SAS Autoreg procedure[17] was applied to the daily incidence of these conditions for 46 days before to 7 days after the 8-day aerial insecticide spraying period to test the a priori hypothesis of a significant (2-tailed $P < .05$) upward shift in visits for these conditions across the 8 spraying days or different levels of increase on individual days.

Results

Description of the Epidemic

From May 30, 2012, through December 3, 2012, patients (n = 1162) with any West Nile virus–positive test result (includ-

Figure 1. Human Infections With West Nile Virus (WNV) in Dallas County, Texas



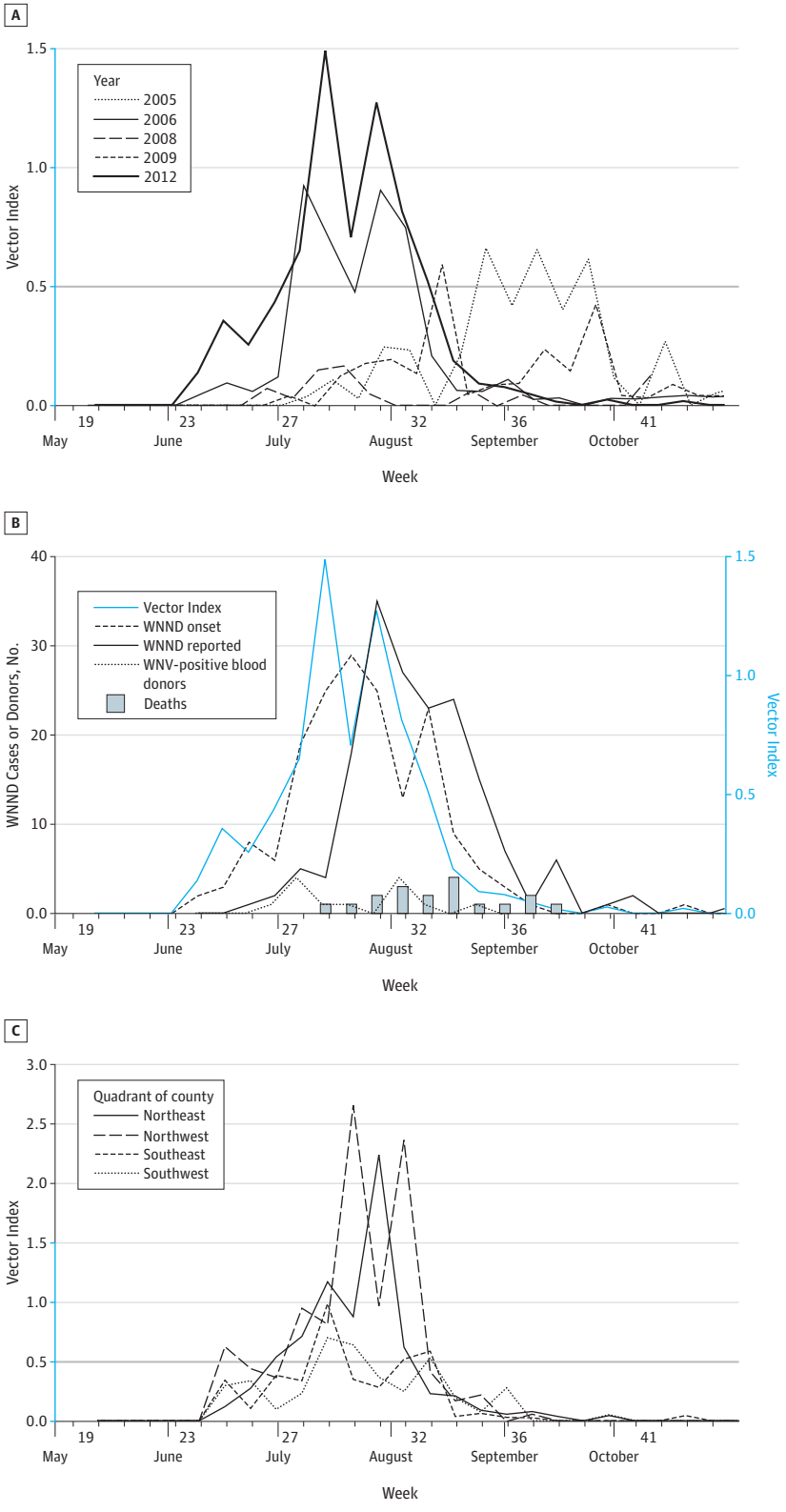
A, Number of West Nile neuroinvasive disease (WNND) cases per year in Dallas County. The first WNV cases occurred in 2002; there were no WNND cases in 2010 and only 1 in 2011. West Nile fever (WNF) cases per year are not shown because the numbers recognized and reported are differentially influenced by the degree of local publicity of WNV epidemics. B, Cases of WNND and WNF in 2012 by week of onset of first symptoms and the number of WNV-positive blood donors identified in Dallas blood banks by week of donation. The 19th death, not shown, occurred in January 2013. Centers for Disease Control and Prevention *Morbidity and Mortality Weekly Report* week numbers are reported beneath the horizontal axis.

ing IgG-positive only) were reported to the health department; 615 met laboratory case criteria, and 398 cases of West Nile virus illness with 19 deaths were confirmed by clinical review in residents of Dallas County, a 2257-km^2 area with a population of 2.4 million.[11] This record-setting urban outbreak followed relatively low numbers of West Nile virus infections in this area during the previous 5 years and only 1 infection during the prior 2 years (**Figure 1**A). Symptoms of the first 19 cases of WNND in 2012 began in June (Figure 1B), a month earlier than in most prior seasons (**Figure 2**A); thereafter, the number of new cases escalated rapidly.

The demographic and clinical characteristics of the patients were similar to those reported in previously described West Nile virus outbreaks (**Table 1**).[18] The outbreak included 173 patients with WNND and 225 with West Nile fever. Patients with WNND were older and more likely male and white than the Dallas County population; 96% were hospitalized; 35% required intensive care; 18% required assisted ventilation; and the case-fatality rate was 10% (Table 1).

Cases of West Nile fever increased later in the season, following intense publicity over the epidemic and mounting numbers of deaths (Figure 1B). Seventeen presumptive viremic blood donors were also identified (Figure 1B), more than twice the number reported in 2006, the second-largest outbreak in the county's 11-year experience with West Nile virus infection (Figure 1A). The overall WNND incidence rate in Dallas County was 7.30 per 100 000 residents in 2012, compared with 2.91 in 2006.

Figure 2. Usefulness of the *Culex quinquefasciatus* Species-Specific Vector Index in Predicting Human West Nile Virus (WNV) Infections in Dallas County, Texas



A, Weekly variation in the vector index by year for years with available archival data. Epidemics occurred in 2006 and 2012. In 2005, West Nile neuroinvasive disease (WNND) cases occurred later in the season, concurrent with a rise in the vector index (heavier horizontal dotted line indicates vector index of 0.5) and persistently high mosquito abundance (eFigure 1). B, Cases of WNND in 2012 by week of symptom onset and by week reported to the health department, fatalities by week of death, and West Nile virus–positive blood donors by week of donation. Vector index is depicted with 1 week added to date of trap collection, to approximate the median lag encountered for identification of positive trap results. The interval from symptom onset to reporting of WNND cases was longer at the start of the epidemic because of only weekly WNV testing by the various clinical laboratories but became timelier when the epidemic was recognized. A highly effective intervention around July 7, immediately after the vector index remained above 0.5 (heavier horizontal dotted line) for 2 consecutive weeks in the northern quadrants of the county, could have prevented an estimated 110 additional WNND cases and an additional 12 deaths. C, Weekly vector index in 2012 in the 4 quadrants of Dallas County (see also eFigure 2). Centers for Disease Control and Prevention *Morbidity and Mortality Weekly Report* week numbers are reported beneath the horizontal axis. Y-axis interval shown in blue indicates vector index of 0 to 1.5.

Table 1. West Nile Virus Neuroinvasive Disease (WNND) and West Nile Fever (WNF) Cases by Patient Characteristics

Patient Characteristics	No. (%)			
	WNND (n = 173)	WNF (n = 225)	All Cases (N = 398)	Dallas County Population (n=2 368 139)
Sex				
Men	108 (62.4)	112 (49.8)	220 (55.3)	1 171 002 (49.4)
Women	65 (37.6)	113 (50.2)	178 (44.7)	1 197 137 (50.6)
Age, y				
0-17	2 (1.2)	9 (4.0)	11 (2.8)	654 263 (27.6)
18-24	7 (4.0)	9 (4.0)	16 (4.0)	236 263 (10.0)
25-44	31 (17.9)	58 (25.8)	89 (22.4)	728 028 (30.7)
45-64	56 (32.4)	93 (41.3)	149 (37.4)	541 613 (22.9)
≥65	77 (44.5)	56 (24.9)	133 (33.4)	207 972 (8.8)
Median (range)	61 (3-93)	53 (3-93)	56 (3-93)	33 (0-100+)
Race/ethnicity[a]				
White	113 (65.3)	154 (68.4)	267 (67.1)	784 693 (33.1)
Hispanic	33 (19.1)	31 (13.8)	64 (16.1)	905 940 (38.3)
Black	18 (10.4)	18 (8.0)	36 (9.0)	518 732 (21.9)
Asian	4 (2.3)	3 (1.3)	7 (1.8)	117 797 (5.0)
Other	1 (0.6)	1 (0.4)	2 (0.5)	40 977 (1.7)
Unknown	4 (2.3)	18 (8.0)	22 (5.5)	NA
Clinical presentation				
Fever	173 (100.0)	225 (100.0)	398 (100.0)	
Meningitis[b]	77 (44.5)	NA	77 (19.3)	
Encephalitis[c]	92 (53.2)	NA	92 (23.1)	
Acute flaccid paralysis	1 (0.6)	NA	1 (0.25)	
Cranial nerve palsies	3 (1.7)	NA	3 (0.8)	
Clinical findings and course				
Time between symptom onset and specimen collection, median (range), d	6 (0-34)	8 (0-122)	7 (0-122)	
Duration of hospitalization, median (range), d	7 (1-150)	4 (1-26)	6 (1-150)	
Patients hospitalized	166 (96.0)	50 (22.2)	216 (54.3)	
Total hospital days, all cases	1968	253	2221	
Admitted to intensive care unit	61 (35.2)	6 (2.7)	67 (16.8)	
Mechanical ventilation or BPAP	31 (17.9)	1 (0.4)	32 (8.0)	
Discharged to LTCF or rehabilitation facility	54 (29.5)	4 (1.8)	58 (14.6)	
Fatal[d]	17 (9.8)	2 (0.9)	19 (4.8)	
Clinical laboratory results				
Serum[e]				
IgM-positive	147 (85.0)	218 (96.9)	365 (91.7)	
PCR-positive	1 (0.58)	7 (3.1)[f]	8 (2.01)	
CSF[e]				
IgM-positive	97 (56.1)	NA	NA	
PCR-positive	2 (1.2)	NA	NA	
Pleocytosis (WBC count ≥5 cells/mm^3)	114 (65.9)	NA	NA	
WBC count, median (range), cells/mm^3	88 (2-1759)	NA	NA	
Premorbid medical conditions				
Hypertension	90 (52.0)	NA	NA	
Diabetes	42 (24.3)	NA	NA	
Cancer	28 (16.2)	NA	NA	
Dialysis or chronic kidney disease	19 (11.0)	NA	NA	
Immunosuppressive drugs	11 (6.4)	NA	NA	
Organ transplantation	4 (2.3)	NA	NA	
HIV infection	3 (1.7)	NA	NA	
None of the above reported	59 (34.1)	NA	NA	

Abbreviations: BPAP, bilevel positive airway pressure; CSF, cerebrospinal fluid; HIV, human immunodeficiency virus; LTCF, long-term care facility; NA, not available; PCR, polymerase chain reaction; WBC, white blood cell.

[a] Defined by standard health department case report forms and assessed by interview or medical records.

[b] Defined as fever, pleocytosis, and stiff neck, headache, or photophobia without mental status changes.

[c] Defined as fever and acutely altered mental status (ie, disorientation, confusion, or obtundation lasting >24 hours).

[d] Deaths were reported to Dallas County Health and Human Services by hospitals, physicians, and the Bureau of Vital Statistics and were classified as West Nile virus–associated if West Nile virus was recorded as cause of death in a patient who had met the case definition.

[e] All WNND cases had West Nile virus IgM antibodies or positive PCR assay in either serum or CSF to meet case classification criteria.

[f] Includes 1 symptomatic viremic blood donor.

Table 2. Prediction of the Number of West Nile Neuroinvasive Disease Cases With Onset of Symptoms Each Week by Weekly *Culex quinquefasciatus* Species-Specific Vector Index From Prior Weeks

Parameter[a]	β (95% CI)[b]	*t*	*P* Value	AIC Model Goodness of Fit[c]
Model 1				
Intercept	0.71 (0.17 to 1.24)	2.58	.01	
Vector index with 1-wk lag[d]	2.12 (1.65 to 2.59)	8.92	<.001	132.63
Model 2				
Intercept	0.79 (0.29 to 1.30)	3.07	.002	
Vector index with 2-wk lag	2.03 (1.63 to 2.43)	9.99	<.001	132.90
Model 3				
Intercept	0.84 (0.22 to 1.46)	2.67	.008	
Vector index with 3-wk lag	1.98 (1.53 to 2.44)	8.51	<.001	133.07
Model 4				
Intercept	0.26 (−0.27 to 0.79)	0.97	.33	
Vector index				
With 1-wk lag	1.20 (0.58 to 1.82)	3.80	<.001	
With 2-wk lag	1.21 (0.72 to 1.69)	4.89	<.001	
With 3-wk lag	0.63 (−0.07 to 1.32)	1.77	.08	122.51
Model 5				
Intercept	0.32 (−0.19 to 0.83)	1.21	.22	
Moving average of the vector index with 1, 2, and 3-wk lags	2.97 (2.34 to 3.60)	9.29	<.001	119.63

Abbreviation: AIC, Akaike information criterion.

[a] The 5 negative binomial count regression models test the association of the vector index with the number of West Nile neuroinvasive disease (WNND) cases with different lag periods from vector index to symptom onset, indicated by the vector index lag terms in the model.

[b] Calculated from the quasi-maximum likelihood standard errors. β indicates the regression coefficient measuring the strength of association between the vector index and the number of WNND cases 1 to 3 weeks later as indicated by the independent variables.

[c] A lower score on the AIC indicates a better-fitting model.

[d] One-week lag indicates vector index predicting WNND cases beginning a week later.

Use of the Vector Index to Predict Epidemic West Nile Virus Infection

The first West Nile virus–positive mosquito pool of 2012 was detected in late May, earlier than in typical seasons. In July, weekly mosquito infection rates peaked at 53.0 (95% CI, 38.7 to 73.3) per 1000 female *Cx quinquefasciatus* mosquitoes, and the vector index peaked at 1.49. Compared with nonepidemic years, the vector index began increasing earlier and peaked higher in 2006 and even higher in 2012; the index exceeded 0.5 in June or July only in 2006 and 2012, the years of the earliest and largest outbreaks (Figure 1A, Figure2A, and eFigure 1 [Supplement]).

Sequential increases in the weekly vector index early in the 2012 season significantly predicted the number of patients with onset of symptoms of WNND in the subsequent 1 to 2 weeks (count regression β = 2.97 [95% CI, 2.34 to 3.60]; *P* < .001) (Figure 2B, **Table 2**, and eTable 1A-C [Supplement]). In the 2 northern quadrants of the county (eFigure 2 [Supplement]), the vector index exceeded 0.5 for 2 consecutive weeks by the first week in July and continued rising to very high peaks (northwest, 2.24; northeast, 2.66), whereas in the 2 southern quadrants it exceeded 0.5 only transiently at smaller peaks (southwest, 0.9; southeast, 0.6) before declining (Figure 2C). Because of the time from symptom onset to diagnosis and reporting, the lag between increases in the vector index and receipt of increased numbers of WNND case reports by the health department was 3 to 4 weeks (Figure 2B).

Geospatial Distribution of WNND

In the early phase of the 2012 epidemic (May 30 to June 30), human WNND cases and West Nile virus–positive mosquito traps were widely dispersed throughout the county, with insufficient points to confirm geographic clustering (**Figure 3**A). By July 21, cumulative numbers of WNND cases and West Nile virus–positive traps showed predominance in the northern half of the county (Figure 3B), which intensified thereafter (Figure 3C and eFigure 3 [Supplement]).

The Getis-Ord Gi* statistic identified a high-risk hot spot of census tracts, each surrounded by other census tracts with high age-adjusted WNND incidence rates (**Figure 4**C). The 104 census tracts in the epidemic hot spot were located mostly in the northern half of the county; compared with other areas, these tracts had significantly higher property values, housing densities, and percentages of houses unoccupied (**Table 3**).

Human WNND and West Nile fever cases from the previous 10 years also showed recurring geographical predominance in the northern half of the county (Figure 4A), and the geospatial hot spots of highest risk in the 2006 and 2012 outbreaks largely overlapped (Figure 4B).

Weather Pattern

The 2012 epidemic year was distinguished from the preceding 10 years by the mildest winter, as indicated by absence of hard winter freezes, the most degree-days above daily normal temperature during the winter and spring, the most winter rainfall, the heaviest winter rains (>1 in/d [2.54 cm/d]), warmer summer weather, and less wind during the windy months (eFigure 4 [Supplement]). Similar extremes occurred in 2006 (eFigure 4 [Supplement]).

Stepwise linear regression analysis of weather variables found that the log-transformed annual incidence of WNND from 2002 through 2012 was most strongly associated inversely with the number of winter days with a hard freeze (number of days with low temperature <28°F [−2.2°C] in December through March; β = −0.29 [95% CI, −0.36 to −0.21]; *P* < .001) (**Figure 5** and eFigure 4 [Supplement]). Other signifi-

cantly associated variables were indicators of generally warmer winter temperatures (total heating-degree days in January and February divided by 100: β = −0.59 [95% CI, −0.97 to −0.21]; *P* = .01; total degrees departure from daily average temperature in January through May divided by 100: β = 0.34 [95% CI, 0.10 to 0.58]; *P* = .02; and total rainfall in January through March: β = 0.20 [95% CI, 0.02 to 0.42]; *P* = .10), but these did not remain significant after entry of the number of hard freeze days (eTable 2A-C [Supplement]).

Epidemic Control Measures

The weekly vector index continued increasing through July despite early initiation of vector control measures, including ground-spraying of insecticide from trucks. In August, ground spraying capacity was expanded and aerial spraying was performed from August 16 through August 23 (eFigure 5 [Supplement]).

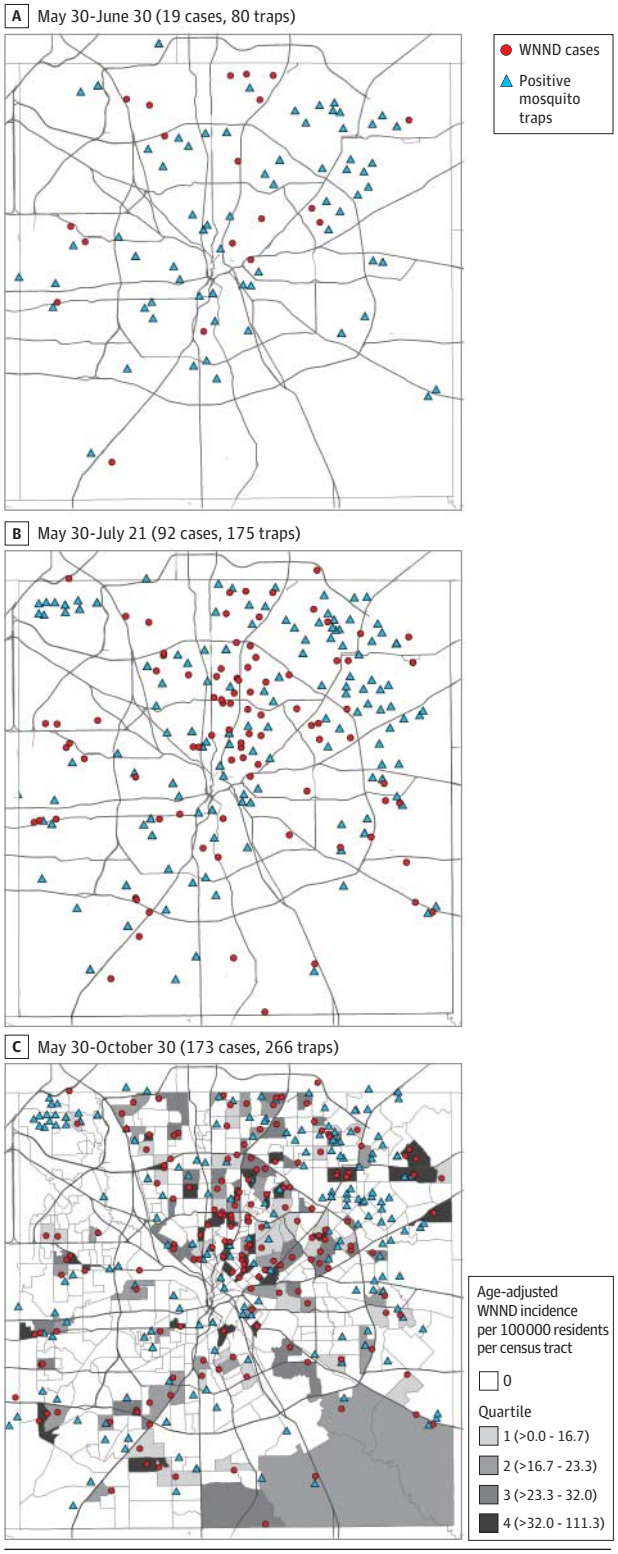
Time-series analysis of data from syndromic surveillance of area emergency departments from 6 weeks before to 7 days after the aerial spraying period showed no increase in visits for lower respiratory tract symptoms, including asthma exacerbations (β = −4.03 [95% CI, −13.76 to 5.70]; *P* = .42), or skin rash (β = −1.00 [95% CI, −6.92 to 4.92]; *P* = .74) during the 8-day spraying period (eFigure 5 and eTable 3A-D [Supplement]).

Discussion

This report identifies several distinguishing features of a large urban West Nile virus outbreak that may assist future prevention and control efforts for vector-borne infections. In the context of local historical data, the 2012 Dallas West Nile virus outbreak was characterized by an earlier appearance of infected mosquitoes and a more rapid rate of increase and higher peak of the weekly vector index. The vector index estimates the average number of West Nile virus-infected mosquitoes collected per trap-night and predicts West Nile virus transmission risk to humans better than other entomologic risk measures of mosquito abundance or mosquito infection rates.[19,20] It has been suggested that increases in the vector index accurately predict increases in onset of human West Nile virus cases 1 to 2 weeks later[7,21] and that analysis of historical mosquito and human infection data in a given locale can identify a threshold in the vector index that accurately predicts imminent large West Nile virus epidemics.[7]

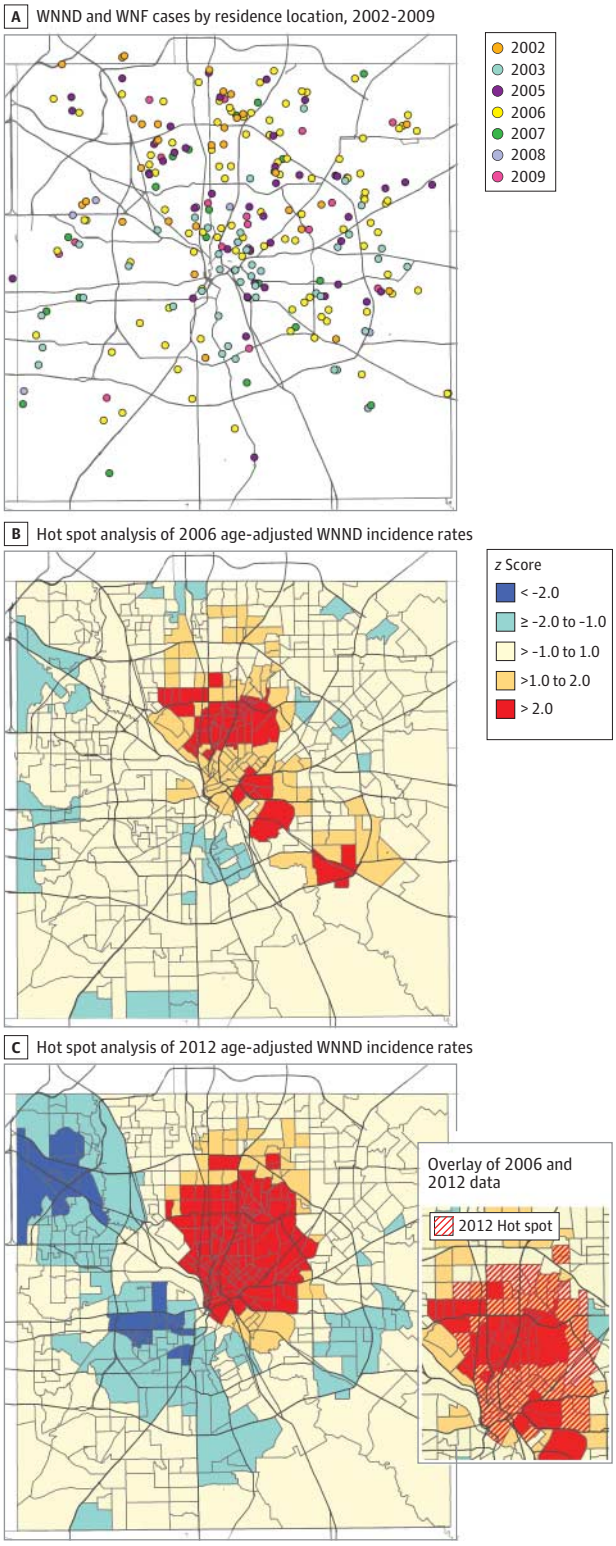
Our analysis of the 2012 epidemic, using robust statistical methods appropriate for time-series count data, identified a strong, statistically significant association between increases in the vector index and increases in the number of WNND cases with symptom onset 1 to 2 weeks later. Moreover, analysis of Dallas County's historical West Nile virus experience found that a vector index threshold of 0.5 in June or July distinguished the 2 largest epidemics from the remaining 9 years, which had minimal human illness. Increases slightly above this threshold in August in 2 of the years were not sustained. If confirmed by additional experience, the actual threshold may differ by locale.

Figure 3. Geospatial Distribution of West Nile Neuroinvasive Disease (WNND) Cases by Date of Onset and Positive Mosquito Traps by Week of Collection, Dallas, Texas, May 30, 2012-October 30, 2012



Locations of gravid mosquito traps that were ever West Nile virus–positive or always negative are shown in eFigure 3.

Figure 4. Geospatial Analysis of West Nile Neuroinvasive Disease (WNND) and West Nile Fever (WNF) Cases, Dallas, Texas, 2002-2009, and Hot Spot Analysis Comparison of the 2006 and 2012 Epidemics



Getis-Ord Gi* *z* scores greater than |2.0| were statistically significant ($P < .05$). A high and positive *z* score value indicates that a census tract is surrounded by other census tracts reporting high West Nile virus disease incidence (ie, part of a hot spot).

Practical use of the vector index is complicated by the short lag of 1 to 2 weeks before symptoms of WNND infections begin and by the additional average 2-week delay in reporting human cases to health authorities from the time needed for diagnosis. With the 2- to 12-day (mean, 7 days) incubation period between mosquito bite and symptom onset, increases in human West Nile virus infections are occurring at the same time as the acceleration in the vector index but are diagnosed and reported to health authorities 3 to 4 weeks later. For the vector index to be operationally useful for guiding mosquito control activities, rapid turnaround of mosquito testing for West Nile virus is necessary. The majority of area traps in 2012 had been tested by viral culture, with positive results lagging a median of 8 days (range, 3-14 days) after collection, and there was no centralized process for collation of these data from the 12 separate agencies engaged in mosquito surveillance and control within the county. Thus, in the 2012 outbreak, the decision to intervene with intensified ground and aerial spraying was prompted by the escalation of reported WNND cases and deaths in late July. Our postseason analysis of mosquito data showed that the vector index had surpassed 0.5 the week ending June 30, by which time onset of symptoms had begun in 19 WNND cases, but only 3 WNND cases had been reported. During the 6 consecutive weeks in which the vector index exceeded 0.5, symptoms had already begun in 117 (68%) of the ultimate 173 WNND cases. Consequently, once the vector index has consistently exceeded a recognized threshold, waiting to initiate augmented vector control activities until significant numbers of human cases and deaths are reported is too late for those measures to prevent the many cases already incubating.

The magnitude of epizootic activity and the consequent numbers of human cases during this outbreak appear to have been precipitated by an extreme weather pattern. Our analysis found that Dallas' largest West Nile virus epidemic seasons in 2006 and 2012 were both high outliers on measures of winter temperatures, total rainfall in winter and early spring, and summer heat. Multivariable analysis suggested that the absence of a hard winter freeze (low temperature <28°F [−2.2°C]) may have been the most important weather factor, but the concordance of all 3 extreme conditions suggests a synergistic effect. Our findings agreed with those from prior studies showing the contribution of warmer temperatures to greater amplification of epizootic West Nile virus activity and increased transmission to humans.[22-26] In Dallas' temperate climate, the effects of the lack of a hard winter freeze on West Nile virus activity would be expected to allow more infected female mosquitoes to survive the winter. Studies have implicated an early spring in allowing a longer period of mosquito-bird transmission with an early start to human infections,[25] which we also observed. Conclusions regarding the influence of precipitation on West Nile virus activity have been mixed,[22-27] with more evidence supporting the importance of drought conditions that have prevailed in Texas for several years, although the availability of spring moisture has been supported.[22,25] Knowledge of climate patterns favoring greater local vector abundance or potential for epizootic amplifica-

Table 3. Multiple Logistic Regression Analysis of Characteristics of the 527 Census Tracts Distinguishing the West Nile Neuroinvasive Disease Hot Spot From the Surrounding Areas[a]

Census Tract Characteristic[b,c]	Descriptive Statistics, Median (IQR)		Logistic Regression Model	
	Census Tracts in the Hot Spot	All Other Census Tracts	OR (95% CI)	AUC
Property values, % of homes worth >$275 000[d]	48.2 (7.4-76.1)	2.0 (0.0-8.6)	1.70 (1.50-1.93)	
Housing density, No. of houses per 1000 m^2	0.99 (0.64-2.13)	0.64 (0.37-0.89)	1.32 (1.18-1.47)	
Unoccupied houses, % of houses unoccupied	12.1 (6.8-16.6)	8.8 (5.5-13.3)	1.24 (1.11-1.37)	0.87

Abbreviations: AUC, area under the receiver operating characteristic curve; IQR, interquartile range; OR, odds ratio.

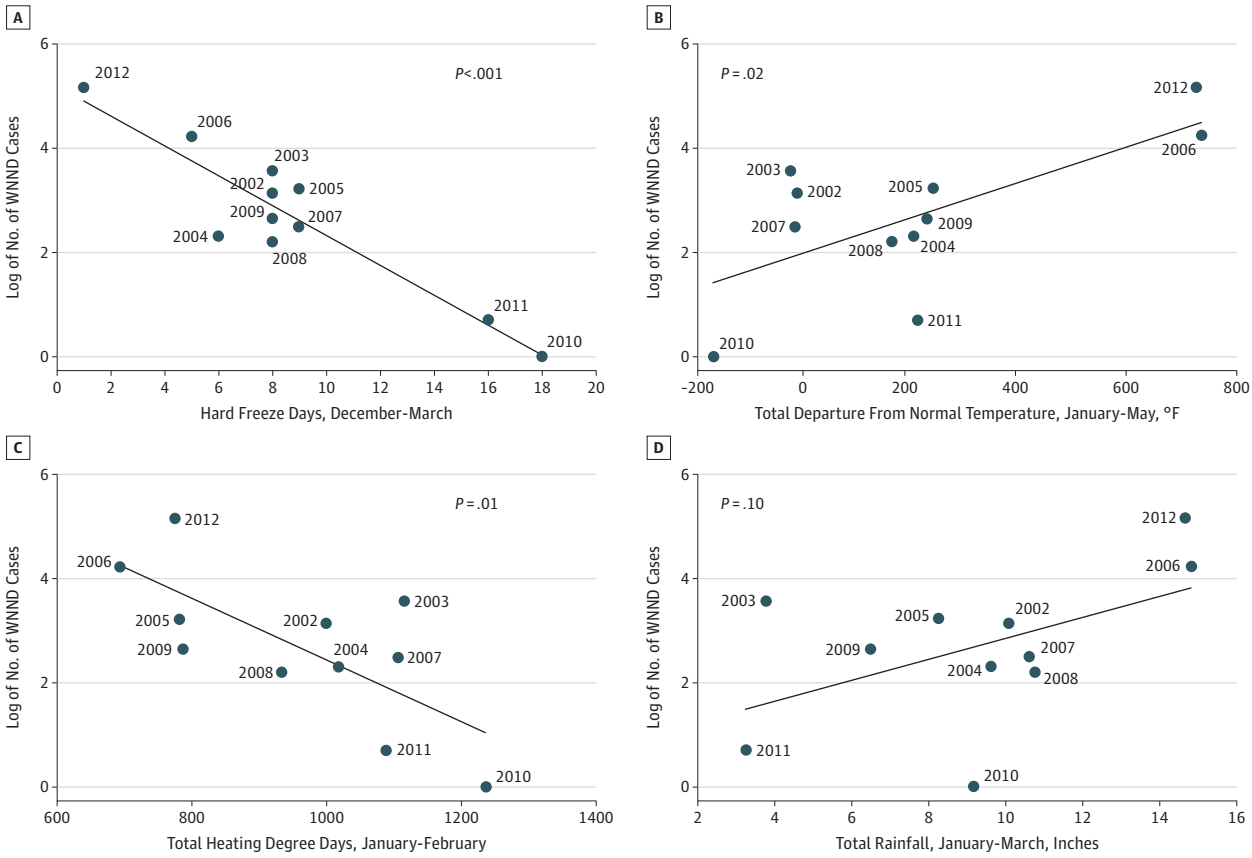
[a] Of the 527 census tracts in Dallas County, 104 (20%) were in the hot spot (Figure 4C).

[b] The independent variables were categorized in deciles; consequently, the OR measures the increase in risk of being in the hot spot zone for every decile increase in the independent variable.

[c] Amount of water-covered area in a census tract and percentage of area covered by water did not differ significantly between census tracts in the hot spot and other areas.

[d] Median household income, significantly higher in the hot spot census tracts, was collinear with property values but not as strongly associated with being in the hot spot.

Figure 5. Association of the Annual Number of West Nile Neuroinvasive Disease (WNND) Cases With Weather Conditions Potentially Predisposing to West Nile Virus Transmission, Dallas County, Texas, 2002-2012



The log-transformed prevalence of WNND cases was regressed on the weather measure, and the line was fit by simple linear regression. A, Daily low temperature below 28°F (−2.2°C) indicates a hard freeze that kills many overwintering mosquitoes, some of which would carry West Nile virus into the next season. B, A highly positive sum of departures from daily normal temperature indicates a generally mild winter and spring. To convert degrees Fahrenheit to degrees Celsius, subtract 32 and multiply difference by 0.556. C, The heating-degree days parameter is the number of degrees below 65°F (18.3°C) each day usually requiring home heating, summed over the winter months January and February; lower winter temperatures retard mosquito activity. D, Greater total rainfall, particularly early in the mosquito breeding season, provides more standing water for amplifying mosquito populations. To convert inches to centimeters, multiply by 2.54.

tion can alert health departments to seasons requiring particularly heightened preseason control measures and expanded vector surveillance.

Our geospatial analysis of WNND cases identified repeated predilection of cases for the northern half of the county over the 11 years studied and a hot spot of particularly high risk

in the same north central area in both the 2006 and the 2012 epidemic years. Our analysis of data from the US Census Bureau's American Community Survey ending in 2011 found that the census tracts in this high-risk hot spot were distinguished from those other areas by higher property values, greater housing density, and a higher percentage of houses unoccupied (reflecting the current economic downturn). These findings agree with those from previous studies showing that West Nile virus outbreaks in metropolitan areas can cluster in neighborhoods with higher income and property values; higher-density housing and less forested areas[28-30]; and more unoccupied houses as a result of mortgage delinquency.[31] Possible explanations include more densely housed neighborhoods having more neglected swimming pools to amplify mosquito populations[31]; densely housed neighborhoods also may sustain lower bird species diversity[32] or the precise mix of bird species causing greater virus amplification ("avian super-spreaders").[33] Our findings did not support an association with the amount of land area covered by water.[24] Whatever the biological explanation, identifying a perennial geographical pattern of human infections should be useful in targeting such areas for more intensive public health prevention measures, including preseason source reduction, larviciding, and education.

Although ultralow-volume aerial spraying has proven effective in quickly curtailing widespread outbreaks of mosquito-borne infections,[34-36] its use during this outbreak generated publicity over possible safety concerns. The ultralow-volume technique effectively kills infected adult mosquitoes with extremely low human exposure levels (<30 mL per acre) of minimally toxic pyrethroid insecticides approved by the Environmental Protection Agency for this purpose.[37,38] Our time-series analyses of the daily incidence of hospital emergency department visits for skin rashes and acute respiratory distress over a 2-month period demonstrated the absence of any detectable increase in these conditions related to the 8-day period of aerial spraying, confirming similar conclusions of safety from prior research.[16,36,39-41] Although the cost of 2 applications of aerial spraying over 875 062 acres in Dallas County was $1 636 348, the direct and indirect costs of the large number of human West Nile virus infections during this outbreak were estimated to exceed $8 million.[42,43]

Conclusions

The resurgence of West Nile virus epidemics in US urban populations in 2012 heightens the importance of more effective measures for minimizing future epidemics. Areas such as Dallas with wide variations in West Nile virus activity between seasons should consider analysis of local West Nile virus history to identify predisposing weather patterns and perennial high-risk geographical areas to efficiently direct preseason prevention measures and surveillance resources. Our findings support incorporating mosquito infection indices into response plans and closely monitoring the mosquito vector index in real time. The goal is to recognize significant increases above historically predictive thresholds of epidemic transmission when augmented mosquito control measures can prevent the most human illness. This requires continuing investments in robust mosquito surveillance programs, including sufficient numbers of traps, rapid testing of mosquitoes, timely collation of information, and establishment of local baseline patterns. Significant numbers of human cases may be reported too late to be a sensitive trigger for expanded intervention during the course of an epidemic.

ARTICLE INFORMATION

Author Contributions: Drs Chung and Haley had full access to all of the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis.
Study concept and design: Chung, Buseman, Luby, Haley.
Acquisition of data: Chung, Buseman, Joyner, Hughes, Haley.
Analysis and interpretation of data: All authors.
Drafting of the manuscript: Chung, Buseman, Joyner, Hughes, Fomby, Haley.
Critical revision of the manuscript for important intellectual content: Chung, Buseman, Joyner, Hughes, Luby, Haley.
Statistical analysis: Chung, Buseman, Joyner, Hughes, Fomby, Haley.
Administrative, technical, or material support: Chung, Buseman, Joyner, Hughes, Luby, Haley.
Study supervision: Chung, Haley.

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REFERENCES

1. Haley RW. Controlling urban epidemics of West Nile virus infection. *JAMA*. 2012;308(13):1325-1326. http://jama.jamanetwork.com/article.aspx?articleid=1355346. Accessed June 5, 2013.

2. Luby JP. St. Louis encephalitis. *Epidemiol Rev*. 1979;1:55-73.

3. Luby JP, Haley RW. Recurrent St. Louis encephalitis infection in residents of a flood plain of the Trinity River, Roosevelt Heights (Dallas, Texas). *Am J Epidemiol*. 1972;96(2):107-113.

4. Petersen LR, Fischer M. Unpredictable and difficult to control—the adolescence of West Nile virus. *N Engl J Med*. 2012;367(14):1281-1284.

5. Turner K, Ferland L; Centers for Disease Control and Prevention (CDC). State electronic disease surveillance systems—United States, 2007 and 2010. *MMWR Morb Mortal Wkly Rep*. 2011;60(41):1421-1423.

6. Division of Notifiable Diseases and Healthcare Information. 2012 Nationally Notifiable Diseases and Conditions and Current Case Definitions. Centers for Disease Control and Prevention website. wwwn.cdc.gov/nndss/document/2012_Case%20Definitions.pdf. 2012. Accessed June 5, 2013.

7. Nasci RS, Doyle M, Biggerstaff BJ, LeBailly A. Calculation and Application of a Vector Index (VI) Reflecting the Number of WN Virus Infected Mosquitoes in a Population. Presented at: 71st Annual Meeting of the American Mosquito Control Association; April 3-7, 2005; Vancouver, British Columbia, Canada. www.colorado.gov/cs/Satellite/CDPHE-DCEED/CBON/1251607766375. Accessed June 5, 2013.

8. Jones RC, Weaver KN, Smith S, et al. Use of the vector index and geographic information system to prospectively inform West Nile virus interventions. *J Am Mosq Control Assoc*. 2011;27(3):315-319.

9. Kwan JL, Park BK, Carpenter TE, Ngo V, Civen R, Reisen WK. Comparison of enzootic risk measures for predicting West Nile disease, Los Angeles, California, USA, 2004-2010. *Emerg Infect Dis*. 2012;18(8):1298-1306.

10. Biggerstaff BJ. PooledInfRate, version 4.0: a Microsoft(R) Excel(R) add-In to compute prevalence estimates from pooled samples. Centers for Disease Control and Prevention website. www.cdc.gov/westnile/resourcepages /mosqSurvSoft.html. 2009. Accessed June 5, 2013.

11. American FactFinder: The 2010 United States Census. United States Census Bureau website. http://factfinder2.census.gov/faces/nav/jsf/pages /index.xhtml. 2010. Accessed June 5, 2013.

12. Getis A, Ord JK. The analysis of spatial association by use of distance statistics. *Geogr Anal*. 1992;24:189-206. doi:10.1111/j.1538-4632.1992.tb00261.x.

13. Winters AM, Eisen RJ, Delorey MJ, et al. Spatial risk assessments based on vector-borne disease epidemiologic data: importance of scale for West Nile virus disease in Colorado. *Am J Trop Med Hyg*. 2010;82(5):945-953.

14. Local Climatological Data Publication. National Climatic Data Center website. www.ncdc.noaa.gov /IPS/lcd/lcd.html?_page=1&state=TX&stationID=13960&_target2=Next+%3E. 2013. Accessed June 5, 2013.

15. Marsden-Haug N, Foster VB, Gould PL, Elbert E, Wang H, Pavlin JA. Code-based syndromic surveillance for influenzalike illness by *International Classification of Diseases, Ninth Revision*. *Emerg Infect Dis*. 2007;13(2):207-216.

16. Karpati AM, Perrin MC, Matte T, Leighton J, Schwartz J, Barr RG. Pesticide spraying for West Nile virus control and emergency department asthma visits in New York City, 2000. *Environ Health Perspect*. 2004;112(11):1183-1187.

17. MacKinlay AC. Event studies in economics and finance. *J Econ Lit*. 1997;35:13-39. www.jstor.org/stable/2729691?cookieSet=1. Accessed June 5, 2013.

18. Huhn GD, Austin C, Langkop C, et al. The emergence of West Nile virus during a large outbreak in Illinois in 2002. *Am J Trop Med Hyg*. 2005;72(6):768-776.

19. Gujral IB, Zielinski-Gutierrez EC, LeBailly A, Nasci R. Behavioral risks for West Nile virus disease, northern Colorado, 2003. *Emerg Infect Dis*. 2007;13(3):419-425.

20. Division of Vector-borne Diseases, Centers for Disease Control and Prevention (CDC). West Nile Virus in the United States: Guidelines for Surveillance, Prevention, and Control. 4th revision. CDC website. www.cdc.gov/westnile/resources /pdfs/wnvGuidelines.pdf. June 14, 2013. Accessed June 21, 2013.

21. Bolling BG, Barker CM, Moore CG, Pape WJ, Eisen L. Seasonal patterns for entomological measures of risk for exposure to *Culex* vectors and West Nile virus in relation to human disease cases in northeastern Colorado. *J Med Entomol*. 2009;46(6):1519-1531.

22. Ruiz MO, Chaves LF, Hamer GL, et al. Local impact of temperature and precipitation on West Nile virus infection in *Culex* species mosquitoes in northeast Illinois, USA. *Parasit Vectors*. 2010;3(1):19.

23. Chuang TW, Ionides EL, Knepper RG, Stanuszek WW, Walker ED, Wilson ML. Cross-correlation map analyses show weather variation influences on mosquito abundance patterns in Saginaw County, Michigan, 1989-2005. *J Med Entomol*. 2012;49(4):851-858.

24. Walsh MG. The role of hydrogeography and climate in the landscape epidemiology of West Nile virus in New York State from 2000 to 2010. *PLoS One*. 2012;7(2):e30620.

25. Chuang TW, Wimberly MC. Remote sensing of climatic anomalies and West Nile virus incidence in the northern Great Plains of the United States. *PLoS One*. 2012;7(10):e46882.

26. Paz S, Malkinson D, Green MS, et al. Permissive summer temperatures of the 2010 European West Nile fever upsurge. *PLoS One*. 2013;8(2):e56398.

27. Landesman WJ, Allan BF, Langerhans RB, Knight TM, Chase JM. Inter-annual associations between precipitation and human incidence of West Nile virus in the United States. *Vector Borne Zoonotic Dis*. 2007;7(3):337-343.

28. Brown HE, Childs JE, Diuk-Wasser MA, Fish D. Ecological factors associated with West Nile virus transmission, northeastern United States. *Emerg Infect Dis*. 2008;14(10):1539-1545.

29. Gómez A, Kilpatrick AM, Kramer LD, et al. Land use and West Nile virus seroprevalence in wild mammals. *Emerg Infect Dis*. 2008;14(6):962-965.

30. Rochlin I, Turbow D, Gomez F, Ninivaggi DV, Campbell SR. Predictive mapping of human risk for West Nile virus (WNV) based on environmental and socioeconomic factors. *PLoS One*. 2011;6(8):e23280.

31. Reisen WK, Takahashi RM, Carroll BD, Quiring R. Delinquent mortgages, neglected swimming pools, and West Nile virus, California. *Emerg Infect Dis*. 2008;14(11):1747-1749.

32. Allan BF, Langerhans RB, Ryberg WA, et al. Ecological correlates of risk and incidence of West Nile virus in the United States. *Oecologia*. 2009;158(4):699-708.

33. Hamer GL, Chaves LF, Anderson TK, et al. Fine-scale variation in vector host use and force of infection drive localized patterns of West Nile virus transmission. *PLoS One*. 2011;6(8):e23767.

34. Carney RM, Husted S, Jean C, Glaser C, Kramer V. Efficacy of aerial spraying of mosquito adulticide in reducing incidence of West Nile virus, California, 2005. *Emerg Infect Dis*. 2008;14(5):747-754.

35. Elnaiem DE, Kelley K, Wright S, et al. Impact of aerial spraying of pyrethrin insecticide on *Culex pipiens* and *Culex tarsalis* (Diptera: Culicidae) abundance and West Nile virus infection rates in an urban/suburban area of Sacramento County, California. *J Med Entomol*. 2008;45(4):751-757.

36. Macedo PA, Schleier JJ III, Reed M, et al. Evaluation of efficacy and human health risk of aerial ultra-low volume applications of pyrethrins and piperonyl butoxide for adult mosquito management in response to West Nile virus activity in Sacramento County, California. *J Am Mosq Control Assoc*. 2010;26(1):57-66.

37. Mount GA, Biery TL, Haile DG. A review of ultralow-volume aerial sprays of insecticide for mosquito control. *J Am Mosq Control Assoc*. 1996;12(4):601-618.

38. Clayton JS, Sander TPY. Aerial application for control of public health pests. *Asp Appl Biol*. 2002;66:1-8. www.micron.co.uk/files/aerialcontrol_2002.pdf. Accessed June 5, 2013.

39. Peterson RK, Macedo PA, Davis RS. A human-health risk assessment for West Nile virus and insecticides used in mosquito management. *Environ Health Perspect*. 2006;114(3):366-372.

40. Macedo PA, Peterson RK, Davis RS. Risk assessments for exposure of deployed military personnel to insecticides and personal protective measures used for disease-vector management. *J Toxicol Environ Health A*. 2007;70(20):1758-1771.

41. Preftakes CJ, Schleier JJ III, Peterson RK. Bystander exposure to ultra-low-volume insecticide applications used for adult mosquito management. *Int J Environ Res Public Health*. 2011;8(6):2142-2152.

42. Zohrabian A, Meltzer MI, Ratard R, et al. West Nile virus economic impact, Louisiana, 2002. *Emerg Infect Dis*. 2004;10(10):1736-1744.

43. Barber LM, Schleier JJ III, Peterson RK. Economic cost analysis of West Nile virus outbreak, Sacramento County, California, USA, 2005. *Emerg Infect Dis*. 2010;16(3):480-486.