Combining Mosquito Vector and Human Disease Data for Improved Assessment of Spatial West Nile Virus Disease Risk

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Abstract. Assessments of spatial risk of exposure to vector-borne pathogens that combine vector and human disease data are needed for areas encompassing large tracts of public land with low population bases. We addressed this need for West Nile virus (WNV) disease in the northern Colorado Front Range by developing not only a spatial model for entomological risk of exposure to *Culex tarsalis* WNV vectors and an epidemiological risk map for WNV disease but also a novel risk-classification index combining data for these independently derived measures of entomological and epidemiological risk. Risk of vector exposure was high in the densely populated eastern plains portion of the Front Range but low in cooler montane areas to the west that are sparsely populated but used heavily for recreation in the summer. The entomological risk model performed well when applied to the western, mountainous part of Colorado and validated against epidemiologic data.

INTRODUCTION

West Nile virus (WNV) disease has emerged as a serious problem in the Central Plains and Rocky Mountains with epidemics causing hundreds to thousands of reported human cases in Colorado, Montana, Nebraska, Wyoming, and the Dakotas in 2003 and in Idaho and Utah in 2006 (data from the Centers for Disease Control and Prevention; http://www.cdc.gov/ncidod/dvbid/westnile/). The northern part of the Colorado Front Range, which spans the transition zone from the Central Plains to the Rocky Mountains, was one of the focal points of this epidemic with 3 counties (Larimer, Boulder, Jefferson) accounting for 1,124 reported WNV cases in 2003 and 187 additional cases during 2004–2006. The caseload for this 3-county area notably exceeds that of most eastern states.

Spatial patterns of risk of human exposure along the northern Colorado Front Range to locally occurring WNV vectors such as *Culex pipiens* and, especially, *Culex tarsalis*1–7 are intriguing because this area 1) extends from the western edge of the Central Plains into the eastern edge of the Rocky Mountains and encompasses habitats ranging from prairie through foothills shrub, montane and subalpine forest, and to alpine areas; 2) includes dramatic elevation–climate gradients potentially affecting the ability of *Culex* mosquitoes to establish breeding populations; and 3) exhibits strong spatial clustering of the human population to the plains habitat in the east. *Cx. tarsalis*, because of its high vector efficiency,1,2 common occurrence,4–6,8–11 and willingness to bite mammals7,12,13 is considered a primary vector of WNV to humans in Colorado and indeed the western United States. Along the northern Colorado Front Range, this mosquito occurs commonly in

heavily populated plains areas at low elevations (e.g., the cities of Boulder, Loveland, and Fort Collins).4–6 There is, however, a lack of detailed knowledge regarding the distribution and abundance of *Cx. tarsalis* in montane areas to the west. These montane areas include large tracts of public land (e.g., Rocky Mountain National Park, Roosevelt National Forest) used heavily in the summer for recreational activities by the Front Range population as well as tourists. Information regarding *Cx. tarsalis* in montane areas of the western United States typically has been qualitative and restricted to records of collection sites.14–16 Because montane areas in the northern Colorado Front Range and, indeed, many other parts of the western United States are dominated by public-access lands and have very low population bases, epidemiologic data are of limited use to assess risk of WNV exposure and need to be complemented with models for entomological risk of exposure to *Cx. tarsalis* and other potential WNV vectors.

The primary goal of this study was to create a comprehensive spatial risk model, combining entomological risk of exposure to *Cx. tarsalis* and epidemiological risk of WNV exposure, for a 3-county area in the northern Colorado Front Range extending from prairie landscapes at the western edge of the Central Plains into montane and subalpine/alpine habitats at the eastern edge of the Rocky Mountains. A secondary goal was to explore how the entomological risk model performed, compared with epidemiologic data, when scaled-up from the ecologically and climatically diverse Larimer County model development area to 4 different regions of Colorado: eastern plains, northern Colorado Front Range, southern Colorado Front Range, and western mountains and high plateau.

MATERIALS AND METHODS

Development of entomological risk model: field sampling of *Cx. tarsalis*. Fieldwork targeted 2 habitat-climate-elevation gradients in the central and southern parts of Larimer County: the Poudre River and Big Thompson River corridors (Figure 1). The general climate in this area is characterized by cold winters and hot summers with low humidity, averaging ~ 400 mm of precipitation per year at lower eleva-
mean monthly and annual cooling, heating, and growing degree days; mean monthly and annual precipitation, snowfall, and relative humidity; mean and median annual length of freeze-free period; median Julian date of first and last snowfall) were derived from Geographic Information System (GIS)-based data for 1961–1990 (2 × 2 km spatial resolution; Climate Source LLC, Corvallis, OR) using ArcGIS9.2 (ESRI, Redlands, CA). Climate data layers were generated by Climate Source LLC using the PRISM modeling system and Gaussian filter resolution enhancement. Site-specific data on elevation were derived from the U.S. Geological Survey 30-m digital national elevation dataset. Selected environmental site characteristics are provided in Table 1.

### Development of entomological risk model: model construction

Associations between site-specific long-term climate data (annual and monthly data for 1961–1990) and mean abundance of *Cx. tarsalis* per trap-night during June 20–September 13, 2006 (hereafter referred to as abundance of *Cx. tarsalis*) were explored by multivariate regression models based on data from 13 sites yielding at least 0.2 mosquito per trap-night. This excluded 7 sites located at elevations above 1,950 m and found to yield no or very few mosquitoes (0–0.1 per trap-night). Long-term climate data are useful for recognizing relative differences in climatic conditions between spatial locations and thus can serve as the basis for spatial modeling. Our use of climate data from 1961 to 1990 and mosquito data from 2006 was based on the assumption that differences in climatic conditions between sampling sites in 2006 were consistent with the differences for the long-term averages. This indeed was the case for one key climate factor available both as temperature logger-derived data from 2006 and long-term 1961–1990 GIS-derived data; site-specific mean June–August temperatures in 2006 were strongly correlated with 1961–1990 averages for these months in the same sites (pairwise correlation coefficient = 0.891, N = 8, P = 0.003). Use of long-term climate data available as spatially continuous GIS data layers also enabled development of spatially continuous predictive models for mosquito abundance based on a far wider range of potentially important climate factors than those available for the mosquito sampling year of 2006.

Elevation, climate factors, and mosquito abundance (natural log-transformed data) were all normally distributed (Shapiro–Wilk test; P > 0.05 in all cases). Results for selected environmental variables in univariate tests are shown in Table 2. A model to predict abundance of *Cx. tarsalis* (dependent variable) was constructed using a forward stepwise multiple regression approach including five biologically meaningful covariates (Table 2; mean temperature for April–September; cumulative cooling degree days for June–August; mean relative humidity for March–May; mean precipitation for January–February; snowfall in April) and using a probability to enter covariates of 0.25.

The equation for the resulting model (which was based on the relationship between cooling degree days and abundance of *Cx. tarsalis*) was applied, at a 2 × 2 km spatial resolution, to the cooling degree day data layer using the raster calculator of ArcGIS9.2 to create a continuous data layer predictive of abundance of *Cx. tarsalis*. Inclusion of Boulder and Jefferson counties in this model is justified because ranges for the single covariate included in the model (cooling degree days) are similar in these counties to the range occurring in the Larimer County model development area; the minimum cooling de-
Analysis of the text would require deep reading and understanding of the context, which is not feasible here. However, the text appears to be discussing the abundance of *Cx. tarsalis*, a mosquito species, and its association with climate conditions in Larimer County, Colorado. The text mentions the use of cooling degree day-based models to categorize sites based on mosquito abundance and the creation of an adjusted r^2 value for linear relationships between climate variables and mosquito abundance.

**TABLE 1**

Abundance of *Cx. tarsalis* from late June to mid-September 2006 and selected environmental characteristics for 20 sites in Larimer County, Colorado.

<table>
<thead>
<tr>
<th>Site</th>
<th>Mean no. of <em>Cx. tarsalis</em> per trap-night</th>
<th>Elevation (m)</th>
<th>Temp (°C)</th>
<th>Cooling degree days</th>
<th>Relative humidity (%)</th>
<th>Precipitation (mm)</th>
<th>Snowfall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lee Martinez‡</td>
<td>7.6 ± 11.5</td>
<td>1,510</td>
<td>9.4</td>
<td>495</td>
<td>52</td>
<td>392</td>
<td>1,396</td>
</tr>
<tr>
<td>Namaqua‡</td>
<td>7.3 ± 4.3</td>
<td>1,520</td>
<td>9.3</td>
<td>479</td>
<td>52</td>
<td>366</td>
<td>1,155</td>
</tr>
<tr>
<td>Glade Park‡</td>
<td>4.3 ± 3.7</td>
<td>1,540</td>
<td>9.2</td>
<td>459</td>
<td>52</td>
<td>389</td>
<td>1,147</td>
</tr>
<tr>
<td>Bellvue‡</td>
<td>30.3 ± 58.9</td>
<td>1,560</td>
<td>8.7</td>
<td>450</td>
<td>52</td>
<td>414</td>
<td>1,145</td>
</tr>
<tr>
<td>Picnic Rock‡</td>
<td>2.5 ± 3.3</td>
<td>1,610</td>
<td>7.6</td>
<td>381</td>
<td>53</td>
<td>459</td>
<td>1,143</td>
</tr>
<tr>
<td>Gateway‡</td>
<td>0.4 ± 0.6</td>
<td>1,640</td>
<td>7.7</td>
<td>340</td>
<td>53</td>
<td>443</td>
<td>1,142</td>
</tr>
<tr>
<td>Narrow‡</td>
<td>4.5 ± 7.2</td>
<td>1,690</td>
<td>8.5</td>
<td>388</td>
<td>53</td>
<td>436</td>
<td>1,130</td>
</tr>
<tr>
<td>Viestenz Smith‡</td>
<td>4.6 ± 9.2</td>
<td>1,730</td>
<td>7.8</td>
<td>357</td>
<td>53</td>
<td>456</td>
<td>1,151</td>
</tr>
<tr>
<td>Ouelt‡</td>
<td>0.2 ± 0.4</td>
<td>1,750</td>
<td>6.5</td>
<td>221</td>
<td>54</td>
<td>492</td>
<td>2,244</td>
</tr>
<tr>
<td>Idylwilde‡</td>
<td>0.4 ± 0.8</td>
<td>1,840</td>
<td>7.3</td>
<td>280</td>
<td>54</td>
<td>462</td>
<td>1,679</td>
</tr>
<tr>
<td>Stove Prairie‡</td>
<td>0.3 ± 0.8</td>
<td>1,860</td>
<td>6.0</td>
<td>174</td>
<td>54</td>
<td>496</td>
<td>2,347</td>
</tr>
<tr>
<td>Drake‡</td>
<td>0.2 ± 0.4</td>
<td>1,870</td>
<td>6.8</td>
<td>280</td>
<td>54</td>
<td>467</td>
<td>1,778</td>
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<tr>
<td>Waltonia</td>
<td>0</td>
<td>1,970</td>
<td>6.7</td>
<td>253</td>
<td>54</td>
<td>460</td>
<td>1,762</td>
</tr>
<tr>
<td>Dutch George‡</td>
<td>0.2 ± 0.6</td>
<td>2,000</td>
<td>5.7</td>
<td>153</td>
<td>54</td>
<td>451</td>
<td>2,188</td>
</tr>
<tr>
<td>Big Thompson</td>
<td>0</td>
<td>2,090</td>
<td>6.4</td>
<td>208</td>
<td>54</td>
<td>457</td>
<td>1,764</td>
</tr>
<tr>
<td>Eggers</td>
<td>0.1 ± 0.3</td>
<td>2,110</td>
<td>5.2</td>
<td>96</td>
<td>53</td>
<td>381</td>
<td>1,860</td>
</tr>
<tr>
<td>Sleepy Hollow</td>
<td>0</td>
<td>2,120</td>
<td>6.2</td>
<td>155</td>
<td>54</td>
<td>456</td>
<td>1,743</td>
</tr>
<tr>
<td>Dadd Gulch</td>
<td>0.1 ± 0.3</td>
<td>2,130</td>
<td>4.8</td>
<td>92</td>
<td>53</td>
<td>330</td>
<td>1,853</td>
</tr>
<tr>
<td>Glen Comfort</td>
<td>0</td>
<td>2,220</td>
<td>5.9</td>
<td>74</td>
<td>54</td>
<td>393</td>
<td>1,199</td>
</tr>
<tr>
<td>Bliss</td>
<td>0.1 ± 0.3</td>
<td>2,360</td>
<td>1.9</td>
<td>0</td>
<td>54</td>
<td>465</td>
<td>3,418</td>
</tr>
</tbody>
</table>

*Mean values for 1981–1990 based on GIS-derived data (2 × 2 km spatial resolution); site locations determined with a GPS receiver.
† Cooling degree days are calculated as the number of degree days exceeding a baseline of 65°F (18.3°C).
‡ Sites included in climate-based model for abundance of *Cx. tarsalis*. |

**TABLE 2**

Adjusted r^2 values and statistical significances for linear relationships between monthly or annual long-term (1961–1990) average climate data and abundance of *Cx. tarsalis* for 13 sites in Larimer County, Colorado, from late June to mid-September 2006.

<table>
<thead>
<tr>
<th>Time period</th>
<th>Mean temperature</th>
<th>Cooling degree days</th>
<th>Relative humidity</th>
<th>Precipitation</th>
<th>Snowfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>0.490**</td>
<td>0NS</td>
<td>0.047NS</td>
<td>0.731***</td>
<td>0.541**</td>
</tr>
<tr>
<td>February</td>
<td>0.710***</td>
<td>0NS</td>
<td>0.520**</td>
<td>0.715***</td>
<td>0.532**</td>
</tr>
<tr>
<td>March</td>
<td>0.708***</td>
<td>0NS</td>
<td>0.687***</td>
<td>0.420**</td>
<td>0.491**</td>
</tr>
<tr>
<td>April</td>
<td>0.733***</td>
<td>0NS</td>
<td>0.615***</td>
<td>0.333*</td>
<td>0.665***</td>
</tr>
<tr>
<td>May</td>
<td>0.719***</td>
<td>0.300*</td>
<td>0.670***</td>
<td>0.051NS</td>
<td>0.543**</td>
</tr>
<tr>
<td>June</td>
<td>0.715***</td>
<td>0.754***</td>
<td>-0.046NS</td>
<td>0.083NS</td>
<td>0NS</td>
</tr>
<tr>
<td>July</td>
<td>0.717***</td>
<td>0.754***</td>
<td>0.470**</td>
<td>0.201NS</td>
<td>0NS</td>
</tr>
<tr>
<td>August</td>
<td>0.712***</td>
<td>0.759***</td>
<td>0.529**</td>
<td>0.496**</td>
<td>0NS</td>
</tr>
<tr>
<td>September</td>
<td>0.715***</td>
<td>0.726**</td>
<td>0.516**</td>
<td>0.278*</td>
<td>0.373*</td>
</tr>
<tr>
<td>October</td>
<td>0.683**</td>
<td>0.153NS</td>
<td>-0.091NS</td>
<td>0.369*</td>
<td>0.553**</td>
</tr>
<tr>
<td>November</td>
<td>0.679***</td>
<td>0NS</td>
<td>0.111NS</td>
<td>0.687***</td>
<td>0.461**</td>
</tr>
<tr>
<td>December</td>
<td>0.590**</td>
<td>0NS</td>
<td>0.010NS</td>
<td>0.612**</td>
<td>0.541**</td>
</tr>
<tr>
<td>Annual</td>
<td>0.715***</td>
<td>0.755**</td>
<td>0.796***</td>
<td>0.498**</td>
<td>0.579**</td>
</tr>
</tbody>
</table>

Climate variable-specific data shown in bold were used (as mean or cumulative data for indicated months) in a multivariate forward stepwise regression modeling approach to determine the association between climate conditions and abundance of *Cx. tarsalis*.

† ANOVA: NS, no significant association (P > 0.05); *P < 0.05; **P < 0.01; ***P < 0.001
‡ Cooling degree days are calculated as the number of degree days exceeding a baseline of 65°F (18.3°C).
Colorado Front Range, the southern Colorado Front Range, and the western mountains and high plateau (see Figure 6 for a map showing the area included in each region). Statistical analyses were carried out using the JMP statistical package21 and results were considered significant when \( P < 0.05 \).

**RESULTS**

**Entomological risk model for the Larimer–Boulder–Jefferson area.** We used a forward stepwise regression modeling approach to develop a model capable of explaining variability in abundance of *Cx. tarsalis* (Table 1) from climate data with relevance to mosquito biology and available as GIS data layers at a 2 × 2 km spatial resolution (Table 2; mean temperature for April–September; cumulative cooling degree days for June–August; mean relative humidity for March–May; mean precipitation for January–February; snowfall in April). The resulting model was based on cumulative cooling degree days for June–August (\( x_1 \)) (In *Cx. tarsalis* per trap-night = −3.2485 + 0.0122 \( x_1 \); ANOVA: \( F_{1,11} = 28.22, \text{adjusted } r^2 = 0.758, P < 0.001 \)). Lack-of-fit test indicated that a sufficient number of independent variables (\( N = 1 \)) were included in the model (\( P = 0.41 \)). There was no spatial autocorrelation either for abundance of *Cx. tarsalis* in the sites included in the modeling effort (Moran’s \( I = 0.01, Z[I] = 1.1 \)) or for the residuals of the linear regression of abundance of *Cx. tarsalis* on cooling degree days (\( I = -0.08, Z[I] = 0.0 \)).

The equation for the model predicting abundance of *Cx. tarsalis* was applied to GIS-based cooling degree day data clipped to the Larimer–Boulder–Jefferson area and projected entomological risk of exposure to *Cx. tarsalis* was categorized as low (\(< 1 \) mosquito per trap-night), moderate (1–5 mosquitoes per trap-night), or high (\( > 5 \) mosquitoes per trap-night). Buffers around perceived larval habitat were applied to uniformly include nonirrigated areas located more than 500 m from larval habitat in the lowest risk category. The spatial pattern of areas with high projected entomological risk of exposure to *Cx. tarsalis* in the Larimer–Boulder–Jefferson area is shown in Figure 2. High-risk areas include southeastern Larimer County, eastern Boulder County, and northeastern Jefferson County.

**Epidemiological risk map for the Larimer–Boulder–Jefferson area.** The epidemiological risk map for the Larimer–Boulder–Jefferson area is shown in Figure 3 with 5 risk categories: 0–10, 11–20, 21–40, 41–60, and > 60 WNV disease cases per 100,000 person-years from 2002 to 2006. Census tracts with WNV disease incidences > 60 cases per 100,000 person-years occurred exclusively in the eastern part of the targeted counties, especially from southeastern Larimer County through eastern Boulder County and into the northeastern edge of Jefferson County. Overall, WNV disease in-
incidence decreased from the plains in eastern Larimer and Boulder counties (typically > 40 WNV cases per 100,000 person-years) to montane areas to the west in these counties or to Jefferson County in the south (most commonly < 20 WNV cases per 100,000 person-years).

**Combined entomological and epidemiological risk-classification index for the Larimer–Boulder–Jefferson area.**

We also created a census tract-based risk-classification index for combined entomological and epidemiological risk of exposure to vectors and WNV in the Larimer–Boulder–Jefferson area. This novel risk-classification index is based on percentage coverage by area with high projected risk of exposure to *Cx. tarsalis* and WNV disease incidence and includes 5 risk classes: Very Low, Low, Moderate, High, and Very High (see Table 4 for further description of these risk classes). The risk-classification index map (see Figure 4) indicates that areas with high to very high risk-classification indices cluster from southeastern Larimer County through

![Figure 2](image2.png)  
**Figure 2.** Projected entomological risk of exposure to *Cx. tarsalis* in the Larimer–Boulder–Jefferson area of the northern Colorado Front Range based on a cooling degree day model and where non-irrigated areas located more than 500 m from perceived larval habitat are included in the lowest abundance category. This figure appears in color at www.ajtmh.org.

![Figure 3](image3.png)  
**Figure 3.** West Nile virus disease incidence per 100,000 person-years, 2002–2006, by census tract in the Larimer–Boulder–Jefferson area of the northern Colorado Front Range. This figure appears in color at www.ajtmh.org.

<table>
<thead>
<tr>
<th>Risk-classification index</th>
<th>No. of census tracts</th>
<th>Coverage of census tract by area with high projected risk of exposure to <em>Cx. tarsalis</em></th>
<th>Census tract-based WNV disease incidence per 100,000 person-years, 2002–2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low</td>
<td>29</td>
<td>0–10%</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Low</td>
<td>27</td>
<td>0–10%</td>
<td>&gt; 5</td>
</tr>
<tr>
<td>Low</td>
<td>15</td>
<td>11–50%</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Moderate</td>
<td>28</td>
<td>11–50%</td>
<td>&gt; 5</td>
</tr>
<tr>
<td>High</td>
<td>71</td>
<td>&gt; 50%</td>
<td>&gt; 20</td>
</tr>
<tr>
<td>Very high</td>
<td>42</td>
<td>&gt; 75%</td>
<td>&gt; 40</td>
</tr>
</tbody>
</table>

**Table 4**

Risk-classification index scheme for West Nile virus exposure in Larimer–Boulder–Jefferson based on percentage coverage of census tract by area with high projected risk of exposure to *Cx. tarsalis* and West Nile virus disease incidence.
Boulder County and into northeastern Jefferson County. The western, montane parts of Larimer and Boulder counties and most of Jefferson County were classified as low to very low risk.

Comparison of spatial patterns of entomological and epidemiologic risk in the Larimer–Boulder–Jefferson area. We found a strong association between presence of areas with high projected entomological risk of exposure to *Cx. tarsalis* and West Nile virus in the Larimer–Boulder–Jefferson area. WNV disease incidence was positively associated with percentage coverage (0, 1–33%, 34–67%, 68–100%) by areas with high projected entomological risk (Figure 5A; WNV disease incidences based on combined case and population data for all census tracts falling within a given category of entomological risk). Statistical analysis was based on data from individual census tracts and revealed that WNV disease incidence for census tracts containing areas with high projected entomological risk (median of 17.7 cases per 100,000 person-years; \( N = 212 \) census tracts) was 4-fold higher than for census tracts lacking such areas (median of 4.7 cases per 100,000 person-years; \( N = 41 \) census tracts) \((\chi^2 = 28.60, \text{df} = 1, P < 0.001)\).

Performance of entomological risk model, relative to epidemiologic data, when applied to different regions of Colorado. We also determined how the entomological risk model performed, compared with epidemiologic data, when scaled-up from the ecologically and climatically diverse Larimer County model development area to 4 different regions of Colorado: eastern plains, northern Front Range, southern Front Range, and western mountains and high plateau (Figure 6). Overall, the entomological risk model performed well in the northern Front Range and western mountains and high plateau but very poorly in the eastern plains (Figure 6; WNV disease incidences based on combined case and population data for all census tracts within a region of the state falling within a given category of entomological risk). The percentage of an individual census tract covered by area classified as high projected entomological risk was significantly positively correlated with WNV disease incidence not only for the Larimer–Boulder–Jefferson area \((\rho_e = 0.551, N = 253, P < 0.001)\) but also for an expanded portion of the northern Front Range \((\rho_e = 0.356, N = 427, P < 0.001)\), western Colorado \((\rho_e = 0.740, N = 151, P < 0.001)\), and the southern Front Range \((\rho_e = 0.292, N = 75, P = 0.01)\). In contrast, we found a negative correlation between coverage with high projected entomological risk and WNV disease incidence in the eastern plains \((\rho_e = -0.304, N = 422, P < 0.001)\).

Census tracts in the northern Front Range containing 68–100% area with high projected entomological risk had higher WNV disease incidence among residents (median of 26.9 cases per 100,000 person-years; \( N = 132 \) census tracts) than census tracts either lacking such areas (median of 4.7 cases per 100,000 person-years; \( N = 41 \) census tracts) or with 1–33% coverage (median of 11.4 cases per 100,000 person-years; \( N = 38 \) census tracts) or 34–67% coverage (median of 10.1 cases per 100,000 person-years; \( N = 42 \) census tracts).
logical risk had higher WNV disease incidence among residents (median of 25.8 cases per 100,000 person-years; N = 32 census tracts) than census tracts lacking such areas (median of 0 cases per 100,000 person-years; N = 93 census tracts) or with 1–33% coverage of area with high entomological risk (median of 11.8 cases per 100,000 person-years; N = 17 census tracts) (χ² = 76.95, df = 1, P < 0.001 and χ² = 8.16, df = 1, P = 0.004, respectively). In the southern Front Range, census tracts containing 68–100% area with high projected entomological risk had higher WNV disease incidence among residents (median of 25.7 cases per 100,000 person-years; N = 63 census tracts) than census tracts with 0–33% coverage (median of 9.3 cases per 100,000 person-years; N = 7 census tracts) (χ² = 6.63, df = 1, P = 0.01). In striking contrast, census tracts in eastern Colorado containing 100% area with high projected entomological risk had 6-fold lower WNV disease incidence among residents (median of 6.3 cases per 100,000 person-years; N = 391 census tracts) than census tracts with 0–67% coverage (median of 39.9 cases per 100,000 person-years; N = 20 census tracts) (χ² = 24.08, df = 1, P < 0.001).

**FIGURE 5.** West Nile virus disease incidence per 100,000 person-years, 2002–2006, in the Larimer–Boulder–Jefferson area of the northern Colorado Front Range in relation to (A) percentage of census tract covered by area with high projected entomological risk of exposure to Cx. tarsalis and (B) distance to an area with high projected entomological risk (distance = 0 m if such an area is contained within a specific census tract). WNV disease incidences are based on combined case and population data for all census tracts falling within a given category for coverage of or distance to entomological risk area.
Figure 7 shows the scaled-up spatial model for high projected entomological risk of exposure to *Cx. tarsalis* in relation to census tract-based WNV disease incidence, for the northern Front Range and western Colorado.

Potential impact of climate warming on mosquito abundance along climate-elevation gradients in the northern Front Range. We used data from HOBO loggers operated in 8 sites along the Poudre River during 2006 to estimate the relationship between elevation ($x$) and daily mean temperature during the peak mosquito breeding season in June–August (Figure 8). Based on the linear relationship between daily mean June–August temperature in 2006 ($y$) and elevation ($x$) ($y = 38.64793 - 0.00538x$; $F_{1,6} = 22.76, r^2 = 0.791, P = 0.003$), incremental elevation increases of 100 m along the Poudre River corresponded to an incremental decrease in mean daily June–August temperature in 2006 of 0.5°C per 100-m elevation change unit. It therefore follows that a realistic future climate-warming scenario resulting in mean daily summer
temperature increases of 1–2°C would cause a shift toward current temperature conditions in the future occurring at elevations 200–400 m higher than today. This realistic scenario would most likely result in both expansion in the range of *Cx. tarsalis* toward higher elevations in the Colorado Front Range and increased mosquito abundance near the current upper altitudinal (climate) limit where *Cx. tarsalis* now is present but scarce.

**DISCUSSION**

Spatial assessments of risk of exposure to WNV have tended to focus on either entomological risk of vector exposure or disease risk based on avian or equine WNV surveillance or human case data. However, each of these risk measures has inherent weaknesses. Entomological risk does not account for the importance of human behavior such as use of mosquito repellents. Avian WNV surveillance either requires costly serosurveys or is subject to variability in levels of detection of dead birds. Epidemiologic data from humans only provide reliable information for risk in areas with an adequate population base and typically are based on address of residence rather than likely exposure site. Following earlier efforts for other mosquito-borne arboviruses, several studies have attempted to address these issues by combining entomological risk measures (vector larval habitat, vector abundance, abundance of infected mosquito pools) with either avian WNV surveillance data or human WNV

**FIGURE 7.** Spatial distribution of areas with high projected entomological risk of exposure to *Cx. tarsalis* in the northern Front Range and western Colorado in relation to census tract-based West Nile virus disease incidence per 100,000 person-years, 2002–2006. This figure appears in color at www.ajtmh.org.

**FIGURE 8.** Relationship between elevation (x) and mean daily temperature during June–August 2006 (y) along the Poudre River corridor in Larimer County (y = 28.64793 – 0.00538x; ANOVA; $F_{1,6} = 22.76$, $r^2 = 0.791$, $P = 0.003$).
disease data (case locations, disease incidence).\textsuperscript{44-49} However, these studies typically either were restricted to risk assessments at a crude county spatial scale\textsuperscript{44,47,48} or failed to generate continuous spatial risk surfaces.\textsuperscript{43,46,49} Perhaps the most complete previous approach comes from a Mississippi study combining spatial continuous environmental data with zip-code–based incidence of WNV disease in humans.\textsuperscript{49} This approach was, however, to some extent impeded by a low case load of human WNV disease (276 cases were reported from Mississippi during the 2002–2003 study period).

To account for the inherent weakness of using either entomological or epidemiological risk measures separately, we developed not only a spatial model for entomological risk of exposure to \textit{Cx. tarsalis} (Figure 2) and an epidemiological risk map for WNV disease (Figure 3) but also a novel risk-classification index combining data for the independently derived measures of entomological and epidemiological risk (Figure 4). This included a 3-county area (Larimer–Boulder–Jefferson) in the northern Colorado Front Range severely afflicted by WNV disease; the 3 counties reported 1,313 human cases from 2002 to 2006. Risk of exposure to \textit{Cx. tarsalis} and WNV was found to be high in the densely populated eastern plains portion of the northern Front Range but low in cooler montane areas to the west that are sparsely populated but used heavily for recreation.

Development of spatial risk models for vector-borne diseases in the western United States that combine entomological and epidemiological risk measures, as previously accomplished for Lyme disease in California,\textsuperscript{41,50} is crucial because this part of the country encompasses large tracts of public land where risk cannot be assessed by epidemiologic data alone due to low population bases. Public lands can, however, be heavily used for recreational purposes and thus represent significant risk of human exposure to vector-borne pathogens. In this study, we were able to use an entomological risk model to demonstrate that Rocky Mountain National Park in far southwestern Larimer County, which receives > 3 million annual visitors with a summer peak in visitor numbers coinciding with vector mosquito and WNV activity in Colorado,\textsuperscript{4,5} currently presents minimal risk of exposure to \textit{Cx. tarsalis} vectors. This was corroborated by the fact that mosquito sampling during the summer of 2006 in 6 locations in a heavily used portion of Rocky Mountain National Park yielded a single \textit{Cx. tarsalis} (L. Eisen, unpublished data).

Our epidemiological risk assessment highlights the importance of using an appropriate spatial scale, such as census tract or zip code, for presentation of incidence of vector-borne diseases in the west, where counties tend to cover large areas and often include considerable ecological and climatic variability.\textsuperscript{40} This is important both to detect areas of low risk within counties with overall high risk (e.g., WNV disease in the Larimer–Boulder–Jefferson area [Figure 3] or Lyme disease in north coastal California\textsuperscript{50}) and to detect small, isolated areas of high risk within counties with overall low risk (e.g., WNV disease in parts of western Colorado [Figure 7] or Lyme disease in southern California\textsuperscript{50}). Additional research efforts relating to spatial ecoepidemiology of WNV disease in Colorado are underway.

Access to census tract-based WNV disease incidence data from 2002 to 2006 for the state of Colorado provided an opportunity to examine how the entomological risk model for the Larimer–Boulder–Jefferson area performed when scaled-up to a larger area of the northern Front Range (Larimer–Boulder–Jefferson–Douglas–El Paso), the southern Front Range, the western Colorado high plateau and mountains, and the eastern Colorado plains. The robust performance, relative to epidemiologic data, of the scaled-up entomological risk model in western Colorado can be attributed to the Larimer County model development area including a climate gradient similar to that for western Colorado. This demonstrates the value of developing spatial models for entomological risk of vector exposure within small but topographically, climatically, and ecologically diverse geographical areas. On the other hand, the Larimer County-derived entomological risk model performed very poorly in the eastern plains, likely because Larimer County includes only a limited portion of the climate variability existing in eastern Colorado. Efforts are underway to generate data for abundance of \textit{Cx. tarsalis} along a climate gradient extending from the Front Range into the eastern plains along the Big Thompson and South Platte rivers. These data will be used to develop a separate model for entomological risk of exposure to \textit{Cx. tarsalis} in the eastern plains.

Finally, our data on abundance of \textit{Cx. tarsalis} along climate–elevation gradients in the Colorado Front Range and the relationship between elevation and temperature in this area suggest that the spatial distribution and abundance patterns of \textit{Cx. tarsalis} are sensitive to climate warming. We expect projected climate warming over the next 50 yr in Colorado, which includes summer temperature increases of 1–2°C,\textsuperscript{22} to shift the cool end of the distribution of \textit{Cx. tarsalis} several hundred meters upward in elevation in the northern Front Range. This, in conjunction with potential changes in availability of mosquito larval habitat following expected decreases in mountain snowpack and subsequent river and stream flooding activity, will impact future patterns of risk of exposure to \textit{Cx. tarsalis} in the Rocky Mountain region. The Colorado Front Range is exceptionally well suited for long-term empirical studies on the effect of climate warming on spatial patterns of distribution and abundance of \textit{Cx. tarsalis} and spatial patterns of presence of WNV in local mosquito populations.

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