

West Nile Virus Mosquito Vectors in North America

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Abstract

In North America, the geographic distribution, ecology, and vectorial capacity of a diverse assemblage of mosquito species belonging to the genus *Culex* determine patterns of West Nile virus transmission and disease risk. East of the Mississippi River, mostly ornithophilic *Culex pipiens* L. complex mosquitoes drive intense enzootic transmission with relatively small numbers of human cases. Westward, the presence of highly competent *Culex tarsalis* (Coquillett) under arid climate and hot summers defines the regions with the highest human risk. West Nile virus human risk distribution is not uniform geographically or temporally within all regions. Notable geographic ‘hotspots’ persist with occasional severe outbreaks. Despite two decades of comprehensive research, several questions remain unresolved, such as the role of non-*Culex* bridge vectors, which are not involved in the enzootic cycle, but may be involved in virus transmission to humans. The absence of bridge vectors also may help to explain the frequent lack of West Nile virus ‘spillover’ into human populations despite very intense enzootic amplification in the eastern United States. This article examines vectorial capacity and the eco-epidemiology of West Nile virus mosquito vectors in four geographic regions of North America and presents some of the unresolved questions.

Key words: West Nile virus, *Culex pipiens*, *Culex restuans*, *Aedes albopictus*, Bridge vectors

Mosquitoes within the genus *Culex* have been implicated as the principal vectors of West Nile virus (WNV) in North America for almost 20 yr (Kramer et al. 2008, Farajollahi et al. 2011, Andreadis 2012). The geographic distribution, ecology, and vectorial capacity of a diverse assemblage of *Culex* species, together with the prevailing environmental and climatic conditions, largely explain continental patterns of West Nile virus transmission and disease risk. For the purpose of this review we have subdivided North America into four geographic regions (Fig. 1) and examined the role of the most dominant *Culex* vectors in the West Nile virus transmission cycle within the ecological and epidemiological settings unique for each region. Additionally, we highlight several unresolved issues concerning the role of vector mosquitoes that require further investigation. This analysis updates and extends previously published reviews (Fonseca et al. 2004; Kramer et al. 2008; Reisen 2010, 2012; Farajollahi et al. 2011; Andreadis 2012) by focusing on the West Nile virus mosquito vector community, their vectorial capacities, and interactions with the environment.

The main mosquito vectors that are the key contributors to West Nile virus transmission cycle vary by region. In the northeastern, mid-Atlantic, and central United States (‘east-central United States’ hereafter; Region 1, Fig. 1), *Culex pipiens* L. and *Culex restuans*

Theobald have been overwhelmingly incriminated as the primary vectors (Kulasekera et al. 2001, Andreadis et al. 2004, Kilpatrick et al. 2005, 2006a, Lampman et al. 2006, Molaei et al. 2006, Hamer et al. 2008, Kramer et al. 2008, Andreadis 2012). The involvement of these species in epidemic transmission of West Nile virus to humans varies seasonally and geographically and may be driven by genetic factors (Huang et al. 2009). *Culex salinarius* (Coquillett) is a highly competent vector that exhibits indiscriminate feeding habits and likely plays a significant role in virus maintenance and transmission to mammals, most notably in coastal areas (Andreadis et al. 2004, Molaei et al. 2006, Anderson et al. 2012a, Andreadis 2012). The east-central geographic region is characterized by intense enzootic amplification of West Nile virus with limited ‘spillover’ into human populations that fluctuates from year to year and usually increases under hotter and drier conditions.

In the southeastern United States (Region 2), the abundance of *Culex quinquefasciatus* (Say) in urban and suburban areas and frequent feedings on both birds and mammals (Molaei et al. 2007), clearly incriminate this species as the primary enzootic and likely epidemic vector (Godsey et al. 2005, Kramer et al. 2008), whereas other species, such as *Cx. salinarius* and *Culex nigripalpus* (Theobald) have been implicated mostly as bridge vectors (Godsey et al. 2005,

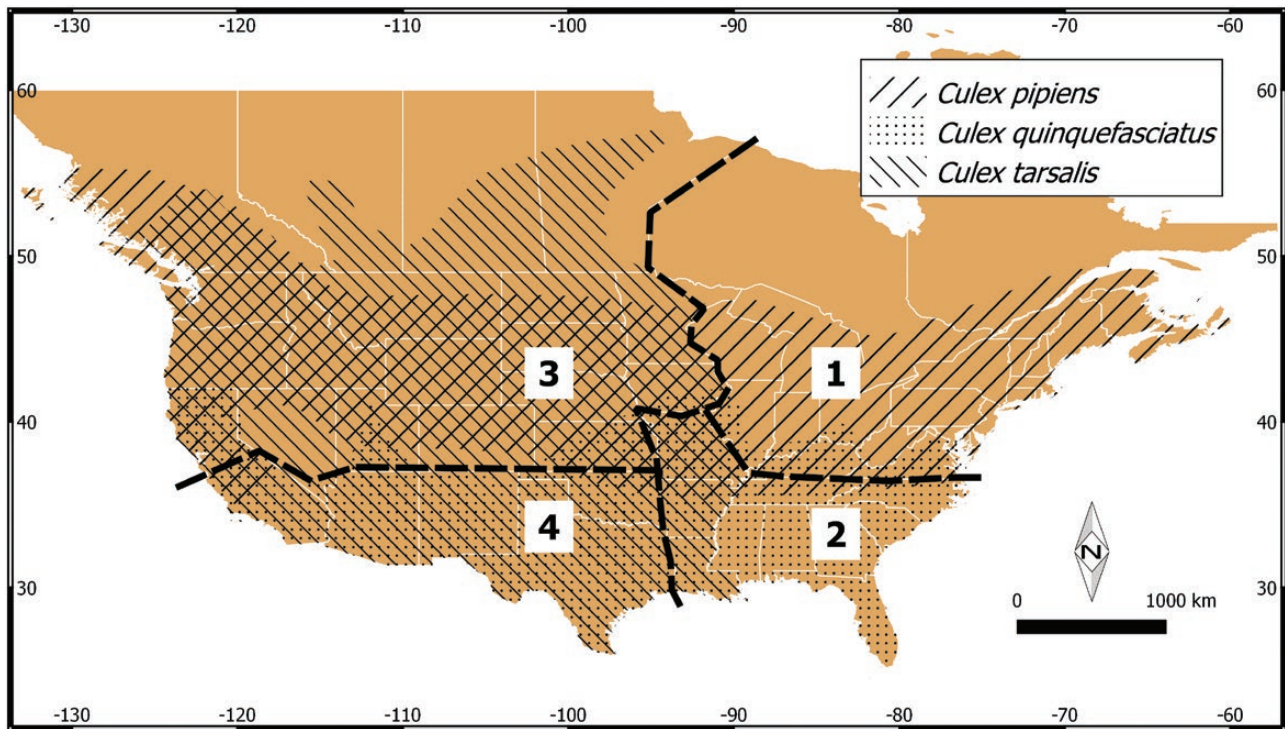


Fig. 1. Four North America regions with the geographic ranges of the primary West Nile virus mosquito vectors (Darsie and Ward 2005, Kothera et al. 2013, Nelms et al. 2013). *Culex tarsalis* occurs east of the Mississippi River, but is rare (Jenkins 1950); it is also scarce in LA, AK, and MO (McNeel and Ferguson 1954). Region 1: *Cx. pipiens*/*Cx. restuans*/*Cx. salinarius*. Bridge vectors: *Cx. pipiens* form *molestus*, *Ae. albopictus*, *Ae. j. japonicus*, *Ae. triseriatus*, *Ae. vexans*. Region 2: *Cx. quinquefasciatus*/*Cx. nigripalpus*. Bridge vectors: *Cx. erraticus*, *Cx. salinarius*, *Ae. albopictus*. Region 3: *Cx. tarsalis*/*Cx. pipiens*. Bridge vectors: *Ae. vexans*, *Cx. salinarius*. Region 4: 'Urban' *Cx. quinquefasciatus*'rural' *Cx. tarsalis*. Bridge vectors: *Ae. albopictus* (urban), *Cx. salinarius*, *Ae. vexans*. Additional explanation found in text.

2013; Vitek et al. 2008). Although less commonly implicated, *Culex erraticus* (Dyer & Knab) also has been found positive for West Nile virus (Godsey et al. 2013) and readily feeds on both mammals and birds (Cohen et al. 2009). Rainy summers in this region appear to mitigate the risk of West Nile virus transmission to humans (Ruiz et al. 2010, Shand et al. 2016).

The incidence of West Nile virus human risk increases west of the Mississippi River as the climate becomes drier and hotter. Intense human transmission in the northern part of the western region (Region 3) is driven by the presence of highly competent and abundant *Culex tarsalis* (Coquillett) that feed on a variety of host species, with *Cx. pipiens* serving as an effective enzootic vector (Curry 2004; Reisen et al. 2004; Bolling et al. 2007, 2009; Winters et al. 2008; Campbell et al. 2013; Anderson et al. 2015; Dunphy et al. 2019). In the southwest (Region 4), transmission is largely driven by *Cx. quinquefasciatus* in urban areas and *Cx. tarsalis* in more rural locales (Reisen et al. 2009, Kwan et al. 2010, Molaie et al. 2010, Godsey et al. 2012, Campbell et al. 2013, Chung et al. 2013, DiMenna et al. 2006). Other *Culex* species including *Cx. salinarius*, *Culex stigmatosoma* (Dyar), and *Culex erythrothorax* (Dyar) may also be involved in the transmission cycle, but based on the comparative paucity of virus detections in these species, they are thought to be of secondary or more localized importance (Pitzer et al. 2009, Molaie et al. 2010, Reisen 2012, DiMenna et al. 2006).

West Nile Virus Testing of Field-Collected Specimens

The national arboviral surveillance system (ArboNet) managed by the Centers for Disease Control and Prevention (CDC) reported

102,215 West Nile virus-positive mosquito pools between 1999 and 2017 (the last year for which data are available at the time of this publication). Of these, 97.4% of the positive pools were comprised of *Culex* species and 1.5% *Aedes* species, with the remainder (1.1%) belonging to eight other mosquito genera (Table 1). In total, 65 species have tested positive for West Nile virus: 26 *Aedes*, 14 *Culex*, 10 *Anopheles*, 6 *Culiseta*, 4 *Psorophora*, and five additional genera with one species each (Table 1) (Fig. 1). We note that the majority of these mosquito pools were tested by molecular methods without isolating actual virus, and detection of West Nile virus RNA in these pools only confirms the presence of virus and not necessarily the ability to transmit the virus.

Comparative percentages of West Nile virus-positive pools by the highest contributing *Culex* and *Aedes* species are shown in Fig. 2. Among those pools identified to the species level, *Cx. pipiens* was more common in the northern Regions 1 and 3, whereas *Cx. quinquefasciatus* predominated in the southern Regions 2 and 4 (Fig. 1). Positive West Nile virus pools obtained from *Cx. tarsalis* were confined to mosquitoes collected in the western United States (Regions 3 and 4).

Among *Aedes* mosquitoes, widespread *Aedes vexans* (Meigen) was the only species from which West Nile virus-positive pools were reported in all four regions of the United States (Fig. 2). *Aedes albopictus* (Skuse) represented the highest proportion of West Nile virus-positive pools, except in northern sections of western United States (Region 3, Fig. 1) where this species is only found sporadically. Other species including *Aedes japonicus japonicus* (Theobald) and *Aedes triseriatus* (Say) collectively represented a small percentage of West Nile virus-positive pools.

Table 1. Generic summary of West Nile virus positive mosquito pools reported to CDC ArboNet from different regions of the United States, 1999–2017

Mosquito genera	East-Central ^a			Southeastern ^b			Western ^c			Southwestern ^d		
	Region 1			Region 2			Region 3			Region 4		
	No. spp.	No. West Nile virus Pools	%	No. spp.	No. West Nile virus pools	%	No. spp.	No. West Nile virus pools	%	No. spp.	No. West Nile virus pools	%
<i>Aedes</i>	16	946	2.0	10	284	1.9	8	87	0.9	11	221	0.8
<i>Anopheles</i>	5	122	0.3	4	55	0.4	3	13	0.1	4	15	0.1
<i>Coquillettidia</i>	1	65	0.1	1	25	0.2	1	3	<0.1	-	-	-
<i>Culex</i>	7	46,767	96.6	7	14,729	96.3	10	9,127	98.4	13	28,884	98.7
<i>Culiseta</i>	4	315	0.7	11	11	0.1	2	44	0.5	3	13	<0.1
<i>Deinocerites</i>	-	-	-	2	2	<0.1	-	-	-	-	-	-
<i>Mansonia</i>	-	-	-	1	4	<0.1	-	-	-	-	-	-
<i>Orthopodomyia</i>	1	6	<0.1	1	1	<0.1	-	-	-	-	-	-
<i>Psorophora</i>	3	30	0.1	3	37	0.2	1	2	<0.1	2	25	0.1
<i>Uranotaenia</i>	1	12	<0.1	1	2	<0.1	-	-	-	-	-	-
Unidentified	-	128	0.3	139	139	0.9	-	3	<0.1	-	98	0.3

^aCT, DC, DE, IL, IN, KY, MA, MD, ME, MI, NH, NJ, NY, OH, PA, RI, VA, VT, WI, WV (1999–2017), also see Fig. 1.

^bAL, AR, FL, GA, LA, MO, MS, NC, SC, TN (2001–2017).

^cCO, IA, ID, KS, MN, MT, ND, NE, NV, OR, SD, UT, WA, WY (2002–2017).

^dAZ, CA, NM, OK, TX (2002–2017).

Vectorial Capacity of *Culex* Mosquitoes

From an eco-epidemiological perspective, vectorial capacity largely defines the role of a species as a vector. Vectorial capacity measures include female abundance, blood-feeding habits, vector competence (the ability to propagate and transmit an infectious agent), extrinsic incubation period (EIP), and adult survival (Freier 1989, Reisen 1989). Each of these components is briefly reviewed below.

Habitat and Abundance

In the east-central United States, immature stages of *Cx. pipiens* and *Cx. restuans* are found, often together, in a variety of aquatic habitats from clear woodland pools to highly polluted waters of sewage treatment plants, farms, and other organically enriched water bodies (Means 1987, Andreadis et al. 2005). These species also inhabit various artificial containers, from tires and buckets to catch basins and storm drains (Geery and Holub 1989). The underground man-made larval habitat is especially important for the West Nile virus transmission cycle in urban and suburban areas. The third species of importance, *Cx. salinarius*, occasionally may be found in small containers (Means 1987, Andreadis et al. 2005, Kaufman et al. 2005), however, its primary habitat is confined to saline, brackish, and adjacent freshwater marshes along the eastern coast, where this species is abundant in both suburban or heavily urbanized areas (Means 1987, Andreadis et al. 2005, Gingrich and Williams 2005, Rochlin et al. 2008a, Bajwa 2018).

A distinct autogenous variant of *Cx. pipiens*, *Culex pipiens* form *molestus* (Forsk.) also occurs in this region (Fonseca et al. 2004, Farajollahi et al. 2011). *Culex pipiens* f. *molestus* has been mostly associated with enclosed and isolated underground habitats in large urban centers including New York City, Chicago, and Boston (Spielman 1967, Kent et al. 2007, Huang et al. 2009, Kothera et al. 2010). However, autogenous *Cx. pipiens* also have been found in suburban and even rural areas suggesting that hybridization between the two forms may occur (Mattingly et al. 1951, Means 1987, Fonseca et al. 2004).

Due to their wide-ranging larval habitats, *Culex* species are among the most abundant mosquitoes found in the east-central United States (Kulasekera et al. 2001, Andreadis et al. 2004, Rochlin et al. 2008b, Verna 2015, Bajwa 2018). The abundance of flood-water or salt marsh *Aedes* and *Coquillettidia* species may exceed *Culex* locally (Andreadis et al. 2004); however, these species are typically more numerous in less developed areas, whereas *Culex* species tend to be abundant in more urbanized settings (Kilpatrick et al. 2005, Rochlin et al. 2008b, Verna 2015). Therefore, in suburban and urban areas, *Cx. pipiens* and/or *Cx. restuans* tend to predominate (Geery and Holub 1989, Savage et al. 2007, Gardner et al. 2013, Johnson et al. 2015), and in heavily urbanized environment of large cities, *Cx. pipiens* is the dominant species (Hamer et al. 2009, Becker et al. 2014, Bajwa 2018). It is notable that large populations of *Cx. salinarius* with frequent West Nile virus infections also have been recorded in Kansas, New Mexico, and Texas (Bolling et al. 2005, Harrison et al. 2009, Ganser and Wisely 2013, DiMenna et al. 2006).

In the southeastern United States, *Cx. quinquefasciatus* utilizes habitats similar to those of *Cx. pipiens*. *Culex quinquefasciatus* has been associated spatially with areas that are urban and suburban and temporally with high temperature (Moise et al. 2018). However, as habitats become increasingly urbanized, the species tends to utilize backyard container habitats, where they compete with container-inhabiting *Aedes* species (Moise et al. 2018). *Culex quinquefasciatus* is extremely common in exposed septic ditches that are abundant throughout Louisiana (Williams and Palmisano 1981) and in sewage

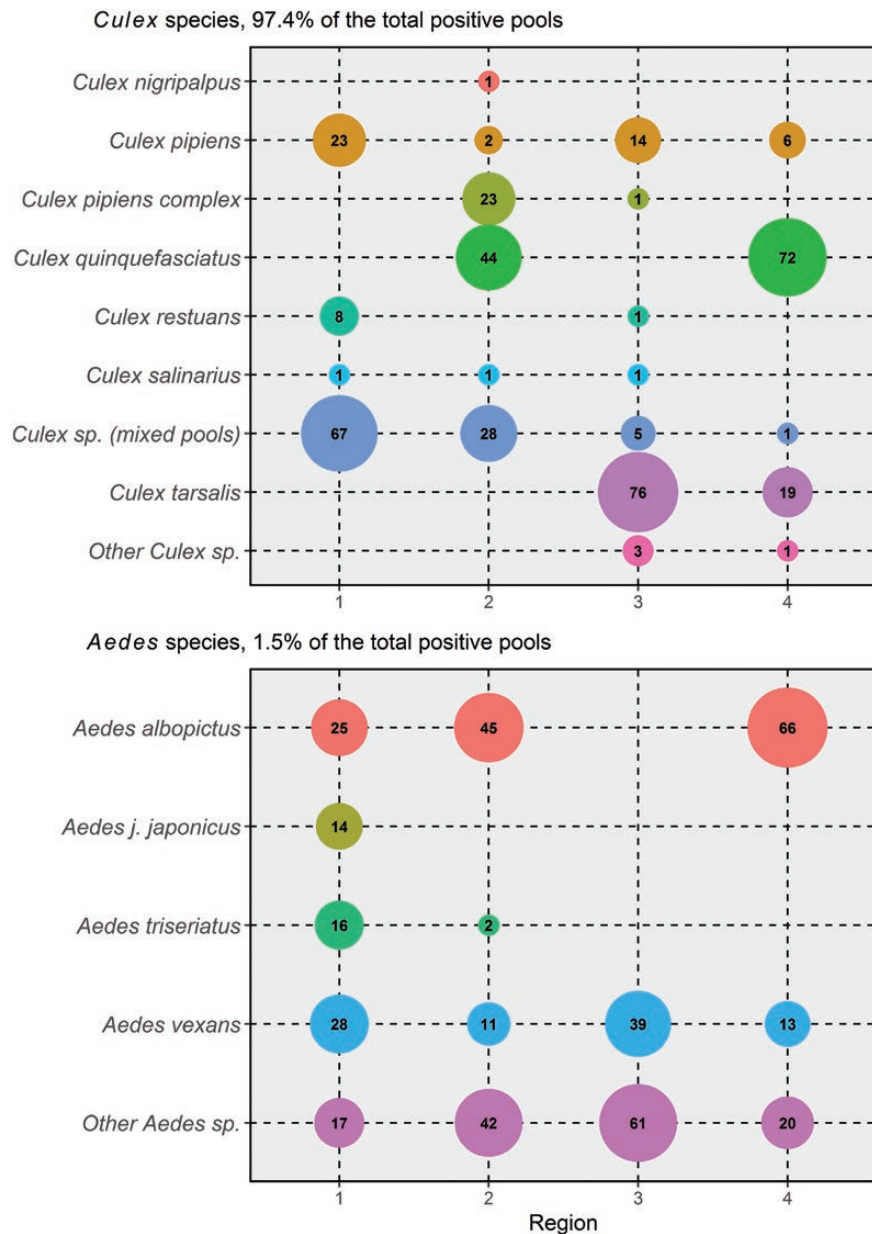


Fig. 2. Comparative percentage of West Nile virus positive mosquito pools obtained from field-collected *Culex* and *Aedes* species reported to CDC ArboNet from the four regions of the United States, 1999–2017. The size of each circle corresponds to the relative percentage (indicated by the number in the center) within each mosquito genus. Only those species with relative percentage > 1% are shown except Region's 3 *Cx. erythrothorax* (2.5%). For geographic Regions 1–4, see Fig. 1. Upper panel: *Culex* species (97.4% of the total positive pools). *Culex pipiens complex* include *Cx. pipiens* and *Cx. quinquefasciatus* hybrids. *Culex sp.* (mixed pools) are mostly composed of unseparated *Cx. pipiens*, *Cx. restuans*, or *Cx. salinarius* mosquitoes. Lower panel: *Aedes* species (1.5% of the total positive pools). Other *Aedes* species category includes those mosquitoes identified to species or generic level.

overflow habitats in Georgia (Calhoun et al. 2007). In Florida, *Cx. quinquefasciatus* is largely associated with urban habitats, whereas *Cx. nigripalpus* is more often found in mixed rural and vegetated habitats (Rey et al. 2006).

In western North America, *Cx. tarsalis* is found in a variety of freshwater habitats, but is most commonly associated with agricultural lands (Bohart and Washino 1978, Reisen et al. 1990, Reisen et al. 2008a). *Culex tarsalis* are less tolerant of pollution than *Cx. pipiens* or *Cx. quinquefasciatus*, and in urban areas their larval habitats are mostly confined to unchlorinated pools, flood channels, and occasional artificial containers. This species can become more abundant in urban areas when suitable larval habitats such as abandoned pools become available (Reisen et al. 2008a). In contrast, *Cx. pipiens*

and *Cx. quinquefasciatus* immatures in the western region, like their counterparts in the east, typically inhabit underground man-made structures such as storm water drains, catch basins, wastewater systems (Su et al. 2003, Bolling et al. 2007, Metzger et al. 2008, Reisen 2012), and peridomestic sources such as gutters, drains, and fountains (Reisen et al. 1990).

Differences in larval habitat requirements are reflected in the distribution of adult populations. In the rural environs of southern California, *Cx. tarsalis* was reported to be the most abundant species (Reisen et al. 2009). By contrast, in heavily urbanized areas such as Los Angeles, *Cx. quinquefasciatus* had the highest relative abundance whereas *Cx. tarsalis* was rarely collected and exhibited a very patchy distribution in the city (Molaei et al. 2010, Kwan et al. 2012,

Thiemann et al. 2012). Similar differences in urban and rural areas were observed in New Mexico, Kansas, and Arizona (Harrison et al. 2009, Pitzer et al. 2009, Godsey et al. 2012, Ganser and Wisely 2013).

There is an apparent latitudinal trend in California whereby the ratio of *Cx. tarsalis* abundance to that of *Cx. pipiens* complex increased from South to North (Barker et al. 2010). *Culex tarsalis* is much more abundant in northern California and Colorado (Bolling et al. 2007, 2009; Campbell et al. 2013) and in the Dakotas and Canadian Great Plains, where this species is thought to be the sole enzootic and epizootic vector (Curry 2004, Bell et al. 2005, Chen et al. 2012, Anderson et al. 2015). In the southwest, *Cx. quinquefasciatus* greatly predominates in urbanized regions of southern California, Arizona, New Mexico, and Texas (Reisen et al. 1990; Dennett et al. 2007; Molaei et al. 2007, 2010; Kwan et al. 2010; Godsey et al. 2012; DiMenna et al. 2006), but not in rural agricultural areas where *Cx. tarsalis* is common (Pitzer et al. 2009, Reisen et al. 2009). An important factor that may limit the vectorial capacity of *Cx. tarsalis* in the southern part of its range is seasonal dynamics. This species' populations peak during the summer in northern latitudes, but in more southern latitudes, it is only commonly found during the cooler months with a short winter diapause, or exhibits bimodal (spring and fall) activity (Bohart and Washino 1978, Reisen et al. 1995, Barker et al. 2010).

Although the relative abundance of *Culex* species is well characterized, few estimates of absolute abundance or density have been published. Reisen et al. (1992) reported that the population density of host-seeking female *Cx. tarsalis* ranged seasonally from 125 to 65,500 females per km² in California and in the same locality, *Cx. quinquefasciatus* reached similarly high absolute abundance. Higher absolute abundances of *Cx. tarsalis* ranging from 56,000 to 155,000 were recorded over the course of the summer by Nelson et al. (1978) at an isolated foothill site in California of less than 1 km².

Host Preference and Bloodfeeding Patterns

Host preference and bloodfeeding of *Culex* vectors have been investigated extensively, yet, despite several points of consensus, considerable disagreements among different studies persist (Fig. 3). In east-central United States (Region 1, Fig. 1), two important

facts have been unequivocally established: 1) *Cx. pipiens* and *Cx. restuans* are primarily ornithophilic and play a major role in the enzootic transmission of West Nile virus among wild bird populations (Andreadis et al. 2004, Apperson et al. 2004, Gingrich and Williams 2005, Lukacik et al. 2006, Molaei et al. 2006, Savage et al. 2007, Hamer et al. 2009, Andreadis 2012); and 2) *Cx. salinarius* is an indiscriminate feeder on a wide range of mammalian and avian hosts in this region and a key West Nile virus bridge vector (Hayes 1961; Crans 1964; Means 1987; Apperson et al. 2002, 2004; Gingrich and Williams 2005; Molaei et al. 2006; Fig. 3).

Much variation and disagreement exist regarding mammalian feeding by *Cx. pipiens* and *Cx. restuans* and their role as bridge vectors, in part, because adults of these two species (and sometimes *Cx. salinarius*) are difficult to distinguish morphologically (Ritchie and Rowley 1981; Means 1987, Harrington and Poulson 2008; Farajollahi et al. 2011). In the northeastern United States, both *Cx. pipiens* and *Cx. restuans* are strongly ornithophilic based on regional bloodmeal identification studies (Apperson et al. 2002, 2004; Molaei et al. 2006; Fig. 3). However, other studies have shown that *Cx. pipiens* and *Cx. restuans* are attracted to mammals (Hayes 1961; Means 1968, 1987; Faraji and Gaugler 2015).

Within *Cx. pipiens*, differences in behavior were attributed to the possible presence of autogenous *Cx. pipiens* f. *molestus*, which are morphologically indistinguishable from *Cx. pipiens* (Spielman 1967, Means 1987). The interbreeding of bird-biting *Cx. pipiens* and mammalian-biting *Cx. pipiens* f. *molestus* occasionally has been observed in this region (Fonseca et al. 2004, Farajollahi et al. 2011) and in other locales (Means 1987, Kent et al. 2007, Huang et al. 2009, Kothera et al. 2010). In an analysis of *Cx. pipiens* from Chicago, IL, which had fed on mammalian hosts, Huang et al. (2009) found a significantly greater proportion of *Cx. pipiens* f. *molestus* ancestry. Spielman (1967) observed that autogenous (mammal feeding) *Cx. pipiens* populations peaked in the late summer or fall, and much later than the anautogenous (bird feeding) populations. Therefore, the observed feeding preference of the *Cx. pipiens* complex could appear to shift during the season from avian to mammalian hosts as proposed by some investigators (Kilpatrick et al. 2006a, 2007) based on earlier studies on *Cx. tarsalis* in western United States (Tempelis

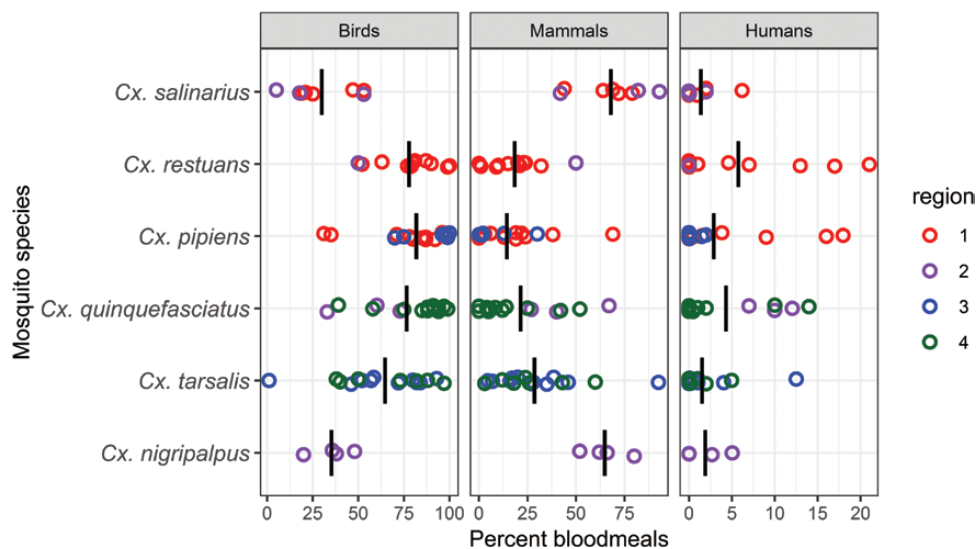


Fig. 3. Bloodmeal analysis of *Culex* mosquitoes in four regions (Fig. 1). The percent of avian, mammal, or human feeding is indicated. Mammalian feeding included human bloodmeals, and both mammalian and human feedings represent their percentage relative to the total number of bloodmeals tested. Each dot corresponds to a separate study or locality (if mosquitoes from multiple localities were tested, Supp Table S1 [online only]). Line designates the mean value for each species. Citations provided in text and in Supp Table S1 (online only).

et al. 1965, 1967). However, this hypothesis was not supported in subsequent studies across the entire region (Kilpatrick et al. 2007; Huang et al. 2008, 2009). Moreover, no clear correlation between *Cx. pipiens* f. *molestus* genetic ancestry and either geographic location (New Jersey vs. New England) or urban/rural gradient was found in an extensive study and caution should be exercised in using hybrid ancestry as the main driver behind the differences in host feeding patterns of *Cx. pipiens* populations (Huang et al. 2008).

An examination of *Cx. pipiens* and *Cx. restuans* populations from more southern and western regions of the United States revealed that the proportion of mammalian bloodfeeding increased (Fig. 3). In the south, *Cx. pipiens* extensively hybridizes with *Cx. quinquefasciatus* (Kothera et al. 2009), which has a higher propensity for feeding on humans (Fonseca et al. 2004). A very detailed analysis conducted at the hybridization zone in Tennessee using molecular species identification (Kothera et al. 2009), concluded that there were no significant differences in mammalian feeding among *Cx. pipiens*, *Cx. quinquefasciatus*, or their hybrids (Savage et al. 2007). A review of more than a dozen studies from the United States, Australia, and Mexico reached similar conclusions (Farajollahi et al. 2011).

Unlike its ecological counterpart, *Cx. restuans* is usually not considered among the potential bridge vectors and is perceived as the most ornithophilic of the common *Culex* in the northeastern and central United States (Andreadis et al. 2004, Hamer et al. 2009, Andreadis 2012). This supposition requires further research because there are no discernable differences between *Cx. pipiens* and *Cx. restuans* in the proportion of mammalian or human bloodmeals (Fig. 3, Farajollahi et al. 2011). In fact, every study outside of the northeastern United States, except one (Edman 1974), identified *Cx. restuans* feeding on humans in addition to other mammals (Fig. 3).

Data from the southeastern United States indicate that *Cx. quinquefasciatus* fed on both avian and mammalian hosts (Edman 1974, Savage et al. 2007, Mackay et al. 2010). It has been hypothesized that *Cx. quinquefasciatus* may show a preference for blood feeding on nestling birds in the spring (Ligon et al. 2009, Burkett-Cadena et al. 2010). However, this species will readily enter dwellings, and feed on available hosts, including humans. Edman (1974) evaluated bloodmeal host preferences of several *Culex* species in Florida. Results showed that *Cx. quinquefasciatus*, *Cx. salinarius*, *Cx. restuans*, and *Cx. nigripalpus* all readily fed on both avian and mammalian hosts. In Florida and Louisiana, human bloodmeals have been detected in *Cx. quinquefasciatus*, *Cx. salinarius*, and *Cx. nigripalpus* (Edman 1974, Mackay et al. 2010).

In the western United States, *Cx. pipiens* is considered an avian feeder, *Cx. quinquefasciatus* feeds on a variety of available hosts, and *Cx. tarsalis* exhibits the most diverse feeding patterns of the three (Bohart and Washino 1978). A summary of the studies conducted between 1940 and 1980 (summarized in Bohart and Washino 1978) and the more recent molecular identifications indicated that *Cx. pipiens* and *Cx. quinquefasciatus* obtained the majority of their bloodmeals from birds (Fig. 3). *Culex tarsalis* obtained a smaller proportion of avian bloodmeals, and also fed on large mammals more often than *Cx. pipiens* in Region 3, and *Cx. quinquefasciatus* in Region 4. In northern California, *Cx. tarsalis* was reported to feed on over a dozen mammalian host species, whereas *Cx. pipiens* fed on single mammalian host or none (Thiemann et al. 2012, Campbell et al. 2013). In southern California, *Cx. quinquefasciatus* fed on a small number of mammalian host species (Thiemann et al. 2012). Among a variety of studies, all three species exhibited similarly low percentages of human bloodmeals.

Seasonal and geographic variations in mammalian feeding have been reported for *Cx. tarsalis* (Tempelis et al. 1965, 1967) and *Cx.*

quinquefasciatus. In a study in Colorado, Kent et al. (2009) showed the percentage of *Cx. tarsalis* mammalian bloodmeals increased twofold from June through August, along with a corresponding increase in human-derived bloodmeals. A similar shift toward increased mammalian feeding in the fall was reported for *Cx. tarsalis* in California (Thiemann et al. 2011) and *Cx. quinquefasciatus* in Texas (Molaei et al. 2007).

Considerable geographic variation was reported from California (Molaei et al. 2010, Montgomery et al. 2011, Thiemann et al. 2012). In the north, over one-quarter of *Cx. tarsalis* bloodmeals were derived from mammals compared to only 2% among *Cx. pipiens* complex species. In central California, both *Cx. pipiens* complex and *Cx. tarsalis* were shown to be mostly ornithophilic with >95% avian-derived bloodmeals. In rural southern California, *Cx. tarsalis* obtained about one-quarter of bloodmeals from mammals, versus less than 10% for *Cx. quinquefasciatus*, including densely populated Los Angeles. These differences were also observed at smaller geographic scales: one-fifth of *Cx. quinquefasciatus* were found feeding on humans at West Nile virus outbreak sites compared to none at control sites in New Mexico (Godsey et al. 2012).

Vector Competence and the EIP

Vector competence is determined by intrinsic or genetic factors that influence the ability of a vector to transmit a pathogen such as West Nile virus (Hardy et al. 1983). Rate of infection is dependent upon the amount of virus ingested. Possible physiological barriers to infection include the midgut and salivary glands (Hardy et al. 1983, Turell et al. 2002a, Colpitts et al. 2012). The percent infected increases as a function of virus titer regardless of temperature and this is related to the midgut infection barrier as measured by comparing the median infectious dose (ID_{50}). Although some studies have used percent blood fed as a baseline, for the purpose of the present review, West Nile virus transmission is presented as the proportion of infected females expectorating virus. All *Culex* species are able to disseminate and transmit West Nile virus after imbibing infectious bloodmeals with a viremia greater than $10^{5.0}$ plaque forming units (pfu) per ml (Komar 2003, Komar et al. 2003, Reisen et al. 2008b; Fig. 4).

In the northeastern United States, *Cx. restuans* mosquitoes are less susceptible to oral infection, but a significantly greater proportion of infected females develop disseminated infections and transmit virus than *Cx. pipiens* (Ebel et al. 2005, Kilpatrick et al. 2010). The vector competence of *Cx. salinarius* is at least as high or higher compared to *Cx. pipiens* and *Cx. restuans* (Fig. 4) based on limited data (Sardelis et al. 2001, Andreadis 2012). *Culex nigripalpus* populations from the southeastern United States exhibit high West Nile virus infection rates, but low transmission rates (Sardelis et al. 2001, Richards et al. 2011). An analysis of *Cx. tarsalis* from California indicated that this species is a more efficient vector, followed by *Cx. pipiens* and *Cx. quinquefasciatus* (Goddard et al. 2002, Turell et al. 2002b, Reisen et al. 2008b). In general, *Cx. salinarius* and *Cx. tarsalis* appear to support higher West Nile virus transmission rates than either *Cx. pipiens*, *Cx. Restuans*, or *Cx. quinquefasciatus* (Fig. 4). Another study estimated the EIP_{50} for *Cx. tarsalis* at 28°C to be 5–7 d, *Cx. pipiens* at 9 d, and *Cx. quinquefasciatus* at 11–12 d (Goddard et al. 2003).

Vector competence can vary geographically and temporally. For example, West Nile virus transmission rates varied from ~0 to 50% for *Cx. pipiens* and from ~0 to 25% for *Cx. restuans* collected from various locations in New York and Massachusetts over a period of several years (Kilpatrick et al. 2010). On the other hand, no observable variations in vector competence for West Nile virus were detected between two populations of *Cx. restuans* from areas with low

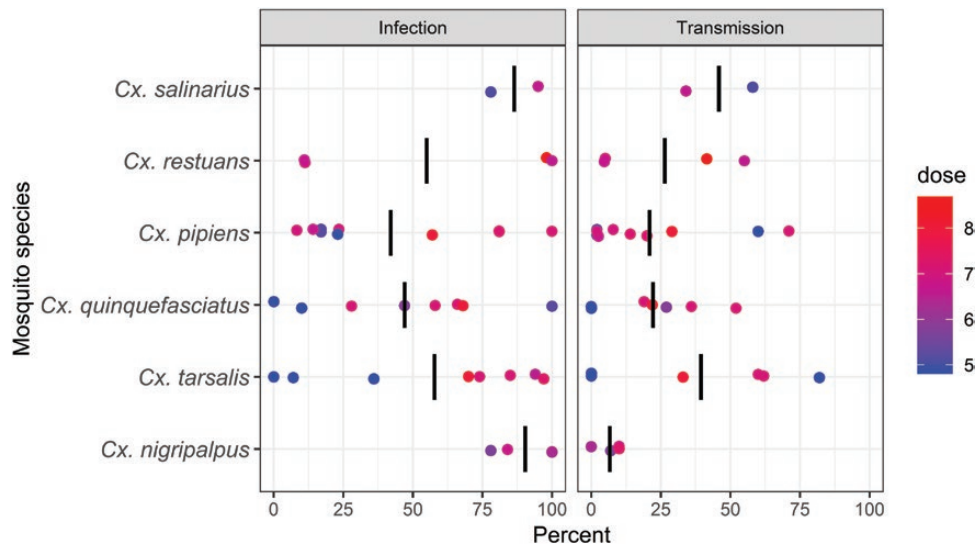


Fig. 4. Vector competence of *Culex* species for West Nile virus. Infection and transmission rates at different oral viremic doses (\log_{10} pfu/ml) are shown. Each dot corresponds to a separate experiment reported in each study. Line designates the mean value for each species. All experiments were conducted under 26–30°C incubation temperature for the duration of 12–15 d. Citations provided in text and in [Supp Table S2](#) (online only).

and high West Nile virus prevalence in Chicago (Mutebi et al. 2012). In California, *Cx. quinquefasciatus* from areas of potential hybridization with *Cx. pipiens* exhibited higher vector competence than ‘pure’ *Cx. quinquefasciatus* further south (Goddard et al. 2002). Southern *Cx. tarsalis* populations had lower West Nile virus competence compared to more northern populations, however, competence fluctuated from year to year (Reisen et al. 2008b).

Temperature can have a considerable effect on the transmission of West Nile virus during extrinsic incubation of the virus. *Culex pipiens* females held at 18°C had consistently lower infection rates compared to those subjected to higher temperatures (Dohm et al. 2002). The relationship between the duration of the West Nile virus EIP and temperature in *Cx. pipiens* was nonlinear, with small increases in temperatures leading to a significant decrease (Kilpatrick et al. 2008). For *Cx. tarsalis*, females held at 14°C transmitted the virus after 36 d, those at 18°C after 22 d, and females held between 26°C and 30°C after as few as 5 d (Reisen et al. 2006).

Vector Survivorship

Longevity of adult female mosquitoes is a critical parameter, because it essentially impacts the size and age of the population that is potentially able to transmit an infectious agent. Variation in mosquito survival may be the dominant factor regulating transmission intensity (Jones et al. 2012). Despite this importance, very little data on *Culex* survival rates have been published. It is also important to note that there are different methodologies to measure mosquito longevity. The majority of studies employ mark-release-recapture (MRR) techniques that provide combined loss due to death and emigration. On the other hand, parity studies measure only loss due to death during a gonotrophic cycle, and cage experiments may produce life tables.

Ciota et al. (2014) has shown that under laboratory conditions, median female longevity decreases with rising temperature. When temperature was increased from 20°C to 24°C, the average lifespan of *Cx. pipiens* was reduced from ~60 d to ~30 d, *Cx. restuans* from ~50 d to less than 25 d, and *Cx. quinquefasciatus* from ~90 d to ~45 d. Similar results were observed with *Cx. pipiens* mosquitoes collected at various altitudes (Ruybal et al. 2016). The largest decrease

in female survival rate occurred between 27°C and 31°C, with less than 30% of females surviving to 9 d at 35°C. Under cooler weather conditions, females of *Cx. pipiens* can be extremely long lived: e.g., 20% of females survived 151 d under ambient temperatures of California’s winter and spring (Strickman and Fonseca 2012).

There are likely many factors that influence survival of adult female *Culex* mosquitoes. Under field conditions, Nelson et al. (1978) estimated daily survival rates of 64 to 77% (including both death and emigration at survival) during summer from the recapture of female *Cx. tarsalis* under open and dry conditions in the foothills of California. Under typical summer field conditions, mean daily survival rate for *Cx. pipiens* females in a suburban area in the mid-Atlantic was 90%, with an average longevity of 10.5 d (Jones et al. 2012). The authors estimated that approximately 4.7% would have likely transmitted West Nile virus on their second feeding on day 10 if they fed on an infected host in their initial feeding on day 3. They subsequently concluded that only a small fraction of mosquitoes would be capable of transmitting West Nile virus. Therefore, any further reduction in adult mosquito survival, such as caused by a severe rainstorm or an adulticide application could decrease or potentially limit virus transmission.

Infection with West Nile virus may also influence survival in mosquitoes. Alto et al. (2014) compared field-collected *Cx. quinquefasciatus* from Gainesville and Vero Beach, FL at 27 and 31°C. They found that at 31°C, infection with West Nile virus caused decreased survival in the Gainesville population compared to those uninfected. Conversely, at 27°C, survival in the Vero population increased when infected with West Nile virus compared to those uninfected. West Nile virus has been shown to alter the cytopathology of mosquitoes and induce additional immune responses (Girard et al. 2006, 2010). Infection with West Nile virus has been shown to increase vacuolization in the midgut epithelium, and apoptosis in salivary gland tissues, which could directly impact survival in mosquitoes. In addition, West Nile virus has been shown to increase upregulation of detoxification genes of *Cx. quinquefasciatus* indicating that West Nile virus might be responsible for oxidative stress. Therefore, the role of the virus on mosquito longevity, both positive and negative, should be further explored.

Aedes Species as West Nile Virus Bridge Vectors

The involvement of *Aedes* species in West Nile virus transmission to humans and other mammalian hosts is uncertain (Andreadis et al. 2004, Kilpatrick et al. 2005, Reisen and Brault 2007, Kramer et al. 2008). Although West Nile virus has been isolated from or detected in 26 different species of *Aedes*, the majority of these species probably play only a minor, if any, role in West Nile virus transmission to humans. Nevertheless, during periods of intense epizootic amplification of the virus, four *Aedes* species may likely serve as bridge vectors (Andreadis et al. 2004, Kilpatrick et al. 2005, Turell et al. 2005, Dennett et al. 2007, Anderson et al. 2015). These include two exotic and aggressive human-biting species that are locally abundant in peridomestic settings where human cases typically occur, *Ae. albopictus* and *Ae. j. japonicus*, and two native, equally aggressive mammalophilic species, the eastern tree hole mosquito, *Ae. triseriatus*, and a floodwater species, *Ae. vexans* (Kulasekera et al. 2001, Andreadis et al. 2004, Kilpatrick et al. 2005, Turell et al. 2005, Erickson et al. 2006, Dennett et al. 2007, Tiawisirup et al. 2008, Molaei et al. 2009, Anderson et al. 2015).

An efficient West Nile virus bridge vector should: 1) exhibit a propensity to blood feed on both avian and mammalian (including human) hosts, 2) be competent to transmit the virus, 3) survive long enough to acquire at least two bloodmeals, and 4) be relatively abundant (summarized in Table 2). The data on the avian feeding for all four *Aedes* species are inconsistent. For *Ae. albopictus*, the proportion of avian bloodmeals has been shown to range from 0 to 17% (Savage et al. 1993, Niebylski et al. 1994, Gingrich and Williams 2005, Richards et al. 2006, Dennett et al. 2007, Faraji et al. 2014). For *Ae. j. japonicus*, direct evidence for feeding on birds is scant, but because West Nile virus has been found in field-collected females, bird feeding is implied (Kaufman and Fonseca 2014). An analysis of field-collected females from Connecticut and New Jersey found this species feeding solely on mammals (Molaei et al. 2008, 2009), however, approximated 15% were reported to feed on birds in Europe (Schönenberger et al. 2016). *Aedes triseriatus* is considered an indiscriminate feeder and studies of populations from the eastern United States have documented the species taking 0–50% of bloodmeals from avian hosts (Apperson et al. 2002, 2004; Molaei et al. 2008). *Aedes vexans* has been shown to feed solely on mammalian hosts (Apperson et al. 2004) or obtain less than 10% of bloodmeals from birds (Hassan et al. 2003, Gingrich and Williams 2005, Molaei and Andreadis 2006, Lujan et al. 2014).

West Nile virus vector competence is influenced by several factors including: the virus titer in the mosquito host, the EIP, and the ambient temperature which can impact the latter. For potential bridge vectors, it is instructive to compare their competence with that of *Cx. pipiens*. Under typical laboratory conditions of ~26°C for

14 d, *Ae. albopictus* and *Ae. j. japonicus* exhibited transmission rates ~1.6 and ~2.5 times higher than *Cx. pipiens* depending on the initial virus dose and the origin of the mosquitoes, whereas *Ae. triseriatus* and *Ae. vexans* had lower infection and transmission rates (~0.4 and ~0.7, respectively) compared to *Cx. pipiens* (Sardelis et al. 2001, 2002; Turell et al. 2001, 2005; Goddard et al. 2002; Tiawisirup et al. 2005, 2008; Erickson et al. 2006).

Field studies on mosquito longevity and survivorship are scarce, although these data are critical for determining the probability of West Nile virus transmission for a bridge vector. Generally, daily survival rates for container-inhabiting *Aedes* species are approximately 90% and much higher than ~70% for the floodwater species *Ae. vexans* (Haramis and Foster 1983, Walker et al. 1987, Jensen and Washino 1994, Niebylski and Craig 1994, Brady et al. 2013). Accurate estimates of relative abundance for container-inhabiting *Aedes* species are difficult to obtain because of low attractiveness of the standard traps, but when appropriate lures are used, *Ae. albopictus* (if present) is the most numerous species, followed by *Ae. j. japonicus* and *Ae. triseriatus* (Anderson et al. 2012b, Rochlin et al. 2016). The native species populations have declined with an increase in the abundance of invasive *Ae. j. japonicus* and *Ae. albopictus* (Rochlin et al. 2013) and immatures of *Ae. j. japonicus* and *Ae. albopictus* often predominate in urbanized environment (Verna 2015). In contrast, floodwater *Ae. vexans* is among the most numerous mosquitoes found in more rural habitats (Andreadis et al. 2004, Gingrich and Williams 2005, Verna 2015), but this adaptable species can be also common in urban and suburban areas throughout the continental United States (Bell et al. 2005, Bolling et al. 2005, Irwin et al. 2008, Harrison et al. 2009, Rochlin et al. 2009, DiMenna et al. 2006, Bajwa 2018).

Vectorial capacity of the four *Aedes* species, and their potential to serve as West Nile virus bridge vectors are shown in Table 2. The two native species, *Ae. vexans* and *Ae. triseriatus* have lower West Nile virus competence compared to the two introduced species. Although *Ae. vexans* is a very common mosquito, it is mostly mammalophilic, and more importantly, it is usually short-lived. Assuming the EIP of 10 d at 26°C (Sardelis et al. 2002), the majority of *Ae. vexans* females may not survive long enough to transmit the virus at the second feeding. However, in western United States, the involvement of this widespread and abundant species in West Nile virus transmission to humans needs to be elucidated (Curry 2004, Bell et al. 2005, Bolling et al. 2007, Ganser and Wisely 2013, Anderson et al. 2015). *Aedes triseriatus* daily survivorship is the highest and it is also an indiscriminate feeder on both birds and mammals, but this species is not common, especially in urban and suburban areas. The introduced species, *Ae. albopictus* and *Ae. j. japonicus*, are highly competent West Nile virus vectors and are abundant in urbanized

Table 2. Vectorial capacity of potential West Nile virus bridge vectors from the genus *Aedes*

Species	Avian feeding	Vector competence compared to <i>Cx. pipiens</i>	Daily survival rate (Median/mean survival time, days)	Abundance	Bridge vector potential
<i>Ae. albopictus</i>	0–17%	Higher	0.9/ (20 d)	High (residential areas), stable	High
<i>Ae. j. japonicus</i>	0% (United States) 15% (Europe)	Higher	(28 d)	Medium-high	Medium
<i>Ae. triseriatus</i>	0–50%	Lower	>0.9	Low-medium, declining in some areas	Low to medium
<i>Ae. vexans</i>	0–10%	Lower	0.7/ (7 d)	Locally high, fluctuating	Low to medium, higher in western United States?

areas. Like *Ae. triseriatus*, their survivorship appears to be high, thereby allowing the majority of females to live through at least two bloodmeals. However, based on scant data, *Ae. j. japonicus* appears to be mammalophilic and thus less likely to acquire the virus from an avian host.

The role of *Ae. albopictus* as a West Nile virus bridge vector has not been completely elucidated and may be more important at different times and places within extensive range of this species. During West Nile virus outbreaks, this species abundance and West Nile virus infection rates in the Houston, Texas, area have been shown to be comparable to those of *Cx. quinquefasciatus* (Dennett et al. 2007). This species' role could be especially significant during intense epizootics of West Nile virus, when the potential for transmission increases considerably.

West Nile Virus Eco-Epidemiology in Relation to Its Vectors

East-Central United States (Region 1)

Culex pipiens, *Cx. restuans*, and *Cx. salinarius* overwinter as adults (Eldridge et al. 1972, Means 1987, Nasci et al. 2001). West Nile virus detection in overwintering females collected from hibernacula (Nasci et al. 2001, Farajollahi et al. 2005, Andreadis et al. 2010), while comparatively rare, provides support for early season initiation of enzootic transmission by *Cx. pipiens* and probably *Cx. restuans* and *Cx. salinarius*. Vertical transmission of West Nile virus has been documented for *Cx. pipiens* (Dohm et al. 2002, Anderson and Main 2006, Anderson et al. 2008) and *Cx. salinarius* (Unlu et al. 2010a, Anderson et al. 2012a). Although the data on *Cx. restuans* are rather scarce, this species was able to transmit closely related St. Louis encephalitis virus to its progeny (Nayar et al. 1986).

During the warm season, West Nile virus is amplified by horizontal transmission with *Culex* mosquitoes feeding on passerine birds such as sparrows in highly urbanized areas (Komar 2003), or, a greater diversity of bird species such as American robins, northern cardinals, northern mockingbirds, and gray catbirds in more suburban and rural locales (Apperson et al. 2002, 2004; Komar 2003; Molaei et al. 2006; Savage et al. 2007; Levine et al. 2016). Perhaps surprisingly, *Culex* mosquitoes rarely acquired their bloodmeals from American crows, which are not as important for enzootic West Nile virus transmission (Kilpatrick et al. 2006b, Molaei et al. 2006, Savage et al. 2007, Hamer et al. 2009). All three *Culex* species typically exhibit similar avian host preferences (Apperson et al. 2002, Molaei et al. 2006, Hamer et al. 2009). American robins were identified as the most common hosts accounting for ~20–70% of bloodmeals (Kilpatrick et al. 2006a, Molaei et al. 2006, Savage et al. 2007, Egizi et al. 2014). It has been postulated that the dispersal of American robins in the late summer drives *Cx. pipiens* to shift to increased mammalian feeding (Kilpatrick et al. 2006a). However, this hypothesis has not been supported by other studies that found no seasonal switch to mammalian feeding (Molaei et al. 2006, Hamer et al. 2009, Levine et al. 2016).

Two main vectors, *Cx. pipiens* and *Cx. restuans*, also differ in their seasonal population dynamics. *Culex restuans* abundance tends to peak earlier than *Cx. pipiens* (Andreadis et al. 2001, 2004; Kunkel et al. 2006; Lampman et al. 2006; Savage et al. 2007, Rochlin et al. 2009; Helbing et al. 2015). The 'crossover' between the two species (Kunkel et al. 2006) typically occurs in July, with *Cx. pipiens* becoming more abundant in July and August. The timing and duration of the crossover period is influenced by ambient temperature and appears to have a significant impact on the seasonal dynamics of these two species in defining the intensity of West Nile virus transmission

(Tokarz and Smith 2019). Notably, while larval surveillance tends to support the crossover observed in the adult populations (Geery and Holub 1989; Gardner et al. 2013), oviposition data do not always show the same trend (Ebel et al. 2005; Jackson and Paulson 2006). Based on the adult mosquito abundance and West Nile virus isolations, *Cx. restuans* is considered an early season enzootic amplification vector, whereas *Cx. pipiens* becomes more important later in the season (Andreadis et al. 2001, 2004; Gingrich and Williams 2005; Savage et al. 2007; Hamer et al. 2009). Which mosquito species serves as a bridge vector facilitating epidemic transmission between birds and humans likely depends on place and time (Andreadis 2012). A risk-assessment model that combined data on mosquito abundance, infection prevalence, vector competence, and biting behavior, estimated that local populations of *Cx. pipiens* and *Cx. restuans* from New Jersey and New York might be responsible for up to 80% of human infections in that region (Kilpatrick et al. 2005). However, the mosquito pools from these areas likely contained a significant proportion of *Cx. salinarius* (Rochlin et al. 2009), perhaps underestimating the contribution of this species.

Culex restuans role in epidemic transmission remains enigmatic. Although the abundance of this species may decline in the late summer, it is still comparable to the other two *Culex* species suggesting that it may contribute to human disease risk (Rochlin et al. 2009, Johnson et al. 2015). Under this scenario, *Cx. pipiens*, *Cx. restuans*, and *Cx. salinarius* may all serve as West Nile virus bridge vectors within location and time specific context.

Southeastern United States (Region 2)

In this region, *Cx. quinquefasciatus* is abundant living in close proximity to humans in urban and suburban habitats and readily enters homes feeding indoors. Unlike *Cx. pipiens*, *Cx. quinquefasciatus* does not undergo diapause, making it incapable of surviving harsh winters (Meuti et al. 2015). West Nile virus transmission by this species is likely driven by reservoir host abundance and dynamics. In Louisiana, models have shown that West Nile virus infection rates were positively correlated with increasing human population densities and negatively correlated with increasing biodiversity of non-passerine birds (Ezenwa et al. 2006). Contact rates with nestling birds in the spring may be an important contributor to West Nile virus activity in the south (Robertson and Caillouët 2016). However, in Atlanta, host preference shifts were observed from feeding on American robins in the early season to northern cardinals in the late season (Levine et al. 2016). It was speculated that this host shift and change in diversity to less competent reservoirs, have helped suppress West Nile virus transmission in the area (Levine et al. 2017).

One of the factors influencing outbreaks of West Nile virus in Florida includes spring drought followed by summer wetting (Shaman et al. 2005), where drought brings both avian hosts and vector mosquitoes in close proximity. In Mississippi, where West Nile virus human incidence is high, road and stream density have been shown to be positively correlated with West Nile virus human cases (Cooke et al. 2006), which is not surprising, given their importance in *Cx. quinquefasciatus* larval habitat types. In addition, density of *Cx. quinquefasciatus* has been positively correlated with vegetation conducive to nestling bird habitats (Sallam et al. 2016). Therefore, climate and availability of habitat in the south, especially as it pertains to bringing avian hosts and vectors together, likely contributes greatly to the seasonal dynamics of West Nile virus transmission.

It has been proposed that reptiles, such as alligators, may serve as potential reservoir hosts in the southeast, given that viremia titers exceed levels high enough to infect *Cx. quinquefasciatus* (Klenk et al.

2004, Jacobson et al. 2005). Interestingly, alligator blood has been detected in both *Cx. quinquefasciatus* and *Cx. nigripalpus* (Unlu et al. 2010b). In addition, python blood has been detected in *Cx. quinquefasciatus* and *Cx. erraticus* in Florida (Reeves et al. 2018). Therefore, the role of reptilian bloodmeals as a source of West Nile virus infection in the southeastern United States could provide further insight into transmission dynamics in more rural areas.

In the areas where *Cx. quinquefasciatus* is scarce or absent, *Cx. nigripalpus* have been implicated as an important West Nile virus vector (Godsey et al. 2005, 2013; Vitek et al. 2008) based on the proximity to humans, the high prevalence of human bloodmeals, and population densities (Sallam et al. 2016). Its role in West Nile virus epidemiology in the south should be further elucidated.

Western United States (Region 3)

Culex tarsalis is sufficiently opportunistic (Fig. 3) to support West Nile virus avian transmission in areas outside of *Cx. pipiens* complex range (Curry 2004, Chen et al. 2012, Anderson et al. 2015). The same highly competent vector plays a major role in both enzootic and epidemic cycles leading to increased West Nile virus human risk in these areas (Chen et al. 2012, DeGroot et al. 2014). In contrast with east-central United States where human cases are associated with urban and suburban areas, in the western United States, West Nile virus human risk is positively correlated with agricultural areas (Bowden et al. 2011, Crowder et al. 2013), perhaps due to the exposure of agricultural workers to mosquito bites. These findings also underscore the difference between the preferred habitat of the main vectors, residential in the east and agricultural areas in the west (Bohart and Washino 1978, Geery and Holub 1989, Reisen et al. 1990, Savage et al. 2007, Reisen et al. 2008a, Gardner et al. 2013, Johnson et al. 2015). In many mid-Western states, such as Kansas, Oklahoma, Iowa, and Texas *Cx. tarsalis* distribution follows a clear west-east gradient, with western and central parts of these states harboring much higher populations of this species (Dennett et al. 2007, Bradford et al. 2008, DeGroot et al. 2008, Harrison et al. 2009, Ganser and Wisely 2013, Nolan et al. 2013, Noden et al. 2015, Dunphy et al. 2019). The same parts of these states are also subject to much higher West Nile virus human risk (DeGroot et al. 2008, Nolan et al. 2013, Noden et al. 2015, Dunphy et al. 2019) supporting the notion that *Cx. tarsalis* is the most effective bridge vector of West Nile virus in North America. Conversely, *Cx. pipiens* appears less important compared to *Cx. tarsalis* where it co-occurs in the western part of its range (Bolling et al. 2007, Winters et al. 2008, Roth et al. 2010, Montgomery et al. 2011, Campbell et al. 2013).

To some extent, the difference between the two species could be attributed to host preferences. American robins are among important avian hosts for *Cx. tarsalis* and *Cx. pipiens* (Kent et al. 2009, Montgomery et al. 2011, Campbell et al. 2013). However, other avian species can be more important depending on abundance and significant geographical variability has been observed (Thiemann et al. 2011, 2012). *Culex tarsalis* feedings on mammals, but not that of *Cx. pipiens*, was greater later in the season (Kent 2009, Montgomery et al. 2011). *Culex tarsalis* host selection flexibility can also contribute to location-specific West Nile virus risk, for example switching to more competent hosts such as corvids would intensify West Nile virus transmission (Thiemann et al. 2012, Campbell et al. 2013).

Landscape and climatic factors also contribute to defining West Nile virus transmission (Reisen 2010). In northwestern United States, the number of West Nile virus infections in humans, horses, and birds were negatively associated with precipitation (Crowder et al. 2013). Plentiful temporal wetlands in the Great Plains (prairie pothole wetlands in the north and playa lakes in the south) are

subject to dry and hot summers concentrating mosquitoes and their avian hosts into small foci with intense virus amplification. This high-risk region is interrupted by the Rocky Mountains towards the west. *Culex tarsalis* abundance decreased rapidly with elevation, and no West Nile virus isolations were made at altitudes higher than 1,600 m (Bolling et al. 2009). The human risk increases again in the valleys of central and southern California that also support intense agricultural production.

Southwestern United States (Region 4)

Culex quinquefasciatus is abundant in urbanized environments, such as Los Angeles, Albuquerque, Phoenix, and Houston, whereas *Cx. tarsalis* is found chiefly in more rural or less populated areas (Dennett et al. 2007, Bradford et al. 2008, Kwan et al. 2010, Molaei et al. 2010, Godsey et al. 2012, Colborn et al. 2013, Nolan et al. 2013, Lujan et al. 2014, DiMenna et al. 2006). These cities contain an extensive network of storm water management structures such as catch basins, storm drains, and retention ponds, highly favorable to *Cx. quinquefasciatus* production (Strickman and Lang 1986, Reisen et al. 1990, Su et al. 2003, Molaei et al. 2007, Metzger et al. 2008, Reisen 2012). In addition to providing larval habitat, underground storm drains can serve as a secure refuge for female mosquitoes to digest bloodmeals and are thus crucial ecological components of the West Nile virus amplification cycle in urbanized areas (Anderson et al. 2006).

There is also a strong climatic connection between the man-made storm water larval habitats and West Nile virus transmission, with rainfall as the key regulatory factor. Excess precipitation flushes larvae out, precludes adult emergence, and diminishes adult survival (Strickman and Lang 1986, Gardner et al. 2012, Jones et al. 2012). Conversely, under drought conditions, avian hosts and vector mosquitoes come into close contact (Shaman et al. 2005, Ruiz et al. 2010, Johnson and Sukhdeo 2013). Frequently, storm water systems retain water replenished by landscape irrigation systems (Reisen et al. 1990). These vector-reservoir congregations around the last 'watering holes' within suburban environments are likely driving increased human risk of contracting West Nile virus during hot and dry periods.

Climatic factors are vital contributors to elevated West Nile virus human risk in the southwestern United States compared to the eastern regions. The main urban vectors, *Cx. pipiens/Cx. restuans* in the north and east and *Cx. quinquefasciatus* in the south and southwest have similar vectorial capacities (Figs. 3 and 4). *Culex quinquefasciatus* obtained a relatively minor proportion of bloodmeals from humans, although this proportion appears to increase southward (Dennett et al. 2007, Molaei et al. 2010, Godsey et al. 2012, Thiemann et al. 2012). However, warmer and drier climate of southwestern United States with prolonged West Nile virus transmission season intensify West Nile virus human risk resulting in larger outbreaks of the disease. Additionally, many parts of southwestern United States harbor significant *Cx. tarsalis* populations driving West Nile virus transmission wherever this species is present (Reisen et al. 2009, Nolan et al. 2013, Lujan et al. 2014, DiMenna et al. 2006). Although *Cx. quinquefasciatus* West Nile virus transmission in large urban centers was typically characterized by episodic outbreaks (Kwan et al. 2010), high West Nile virus epidemic activity was sustained over multiple years in rural areas where *Cx. tarsalis* predominated (Reisen et al. 2009). Other *Culex* species in western United States, such as *Cx. stigmatosoma* and *Cx. erythrothorax* may be involved in the enzootic cycle or serve as a bridge vector, respectively (Goddard et al. 2002, Kwan et al. 2010, Molaei et al. 2010).

Unresolved Questions and Future Directions

In summary, we note several unresolved issues concerning the role of vector mosquitoes for further investigation:

The Role of *Aedes* Bridge Vectors

These vectors are very important from both theoretical and practical (operational vector control) perspectives. Their involvement in West Nile virus may be location and time specific. The most pressing questions concern the role of *Ae. albopictus* in urban outbreaks, and the role of widespread and abundant *Ae. vexans* in both suburban and rural areas, especially in the northeastern and western United States. Another interesting question is why have we observed a reduction in the number of mosquito species found positive for West Nile virus since the initial years following its introduction into the United States? Has the virus really stabilized and found its enzootic, epizootic, and epidemic niche? Or could the large initial detections of West Nile virus positive mosquito pools be attributed to contamination and the lack of expertise/training at the operational level during the formative years? Many mosquito control districts now routinely focus testing on known West Nile virus vectors, which provides rapid data useful for control decisions, but limits the detection of West Nile virus in other species.

Vector Longevity

Mosquito demography including daily survivorship, duration of the gonotrophic cycle (or blood-feeding frequency) and absolute population density are important factors in determining the vectorial capacity for West Nile virus. These data are especially important for the potential bridge vectors. Yet, very few studies have investigated these parameters.

Vector-Host Interactions

Is there a 'crossover' between vector mosquitoes and naïve fledglings susceptible to both bites and West Nile virus infection? Timing of such 'crossover' would be critical for amplification and the spillover of the virus and might be dependent on host species composition (single vs. multibrood species). In addition, could control strategies be used that help break the cycle during this crossover period? Studies that help elucidate this crossover period, could potentially be used to determine an important target period to minimize the impact of West Nile virus.

Low Human Infection Prevalence in the East

Intense epizootics with no or little epidemic transmission have been observed repeatedly in the eastern United States. This epidemiological picture contradicts the entomological risk based on the presence of vectors with high vectorial capacity and considerable human feeding such as by *Cx. pipiens* or *Cx. quinquefasciatus*. If this is a function of a shorter amplification season in the northeast, why are similarly low or even lower incidence rates found in many southeastern states? Perhaps West Nile virus human transmission is more precipitation dependent than generally assumed, with human incidence rates increasing westward in proportion with diminished rainfall? The dynamic factors between vector and host abundance, precipitation, temperature, and humidity still wait to be elucidated and conceptualized. Behavioral and socioeconomic factors may also play a role in determining the human risk.

Increased Incidence of Human Disease in the West

Geographic 'hotspots' of human risk persist in areas such as Upper Midwest, Texas, Mississippi/Louisiana, and some areas in California.

Can the presence of these 'hotspots' be explained by mosquito vectors, host species and host immunity, environmental, socioeconomic, or behavioral factors, or their combination? What role do agricultural practices, such as working at night, play? It is still unclear why these outbreaks occur periodically and tend to shift on micro-geographic scales.

Limited Geographic Coverage

Most West Nile virus research has been conducted in a few states such as California, Illinois, Connecticut, New York, New Jersey, and Florida. Given the local variability in West Nile virus transmission, expanding the geographic bounds of intense research investment seems imperative if we want to understand West Nile virus epidemiology.

In conclusion, much progress in understanding the various aspects of West Nile virus transmission, ecology, and epidemiology have been made since the introduction of the virus to North America in 1999. Intense efforts have been focused on elucidating the role of mosquito vector species, a key component of the West Nile virus transmission cycle important not only from purely academic perspective, but absolutely essential for guiding the practical steps of surveillance and control for the protection of public health. Despite considerable advancements, multiple questions regarding mosquito vectors require further research.

Supplementary Data

Supplementary data are available at *Journal of Medical Entomology* online.

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References Cited

- Alto, B. W., S. L. Richards, S. L. Anderson, and C. C. Lord. 2014. Survival of West Nile virus-challenged Southern house mosquitoes, *Culex pipiens quinquefasciatus*, in relation to environmental temperatures. *J. Vector Ecol.* 39: 123–133.
- Anderson, J. F., and A. J. Main. 2006. Importance of vertical and horizontal transmission of West Nile virus by *Culex pipiens* in the Northeastern United States. *J. Infect. Dis.* 194: 1577–1579.
- Anderson, J. F., T. G. Andreadis, A. J. Main, F. J. Ferrandino, and C. R. Vossbrinck. 2006. West Nile virus from female and male mosquitoes (Diptera: Culicidae) in subterranean, ground, and canopy habitats in Connecticut. *J. Med. Entomol.* 43: 1010–1019.
- Anderson, J. F., A. J. Main, K. Delroux, and E. Fikrig. 2008. Extrinsic incubation periods for horizontal and vertical transmission of West Nile virus by *Culex pipiens pipiens* (Diptera: Culicidae). *J. Med. Entomol.* 45: 445–451.
- Anderson, J. F., A. J. Main, G. Cheng, F. J. Ferrandino, and E. Fikrig. 2012a. Horizontal and vertical transmission of West Nile virus genotype NY99 by *Culex salinarius* and genotypes NY99 and WN02 by *Culex tarsalis*. *Am. J. Trop. Med. Hyg.* 86: 134–139.
- Anderson, J. F., S. McKnight, and F. J. Ferrandino. 2012b. *Aedes japonicus japonicus* and associated woodland species attracted to Centers for

- Disease Control and Prevention miniature light traps baited with carbon dioxide and the Traptech mosquito lure. *J. Am. Mosq. Control Assoc.* 28: 184–191.
- Anderson, J. F., A. J. Main, P. M. Armstrong, T. G. Andreadis, and F. J. Ferrandino. 2015. Arboviruses in North Dakota, 2003–2006. *Am. J. Trop. Med. Hyg.* 92: 377–393.
- Andreadis, T. G. 2012. The contribution of *Culex pipiens* complex mosquitoes to transmission and persistence of West Nile virus in North America. *J. Am. Mosq. Control Assoc.* 28: 137–151.
- Andreadis, T. G., J. F. Anderson, and C. R. Vossbrinck. 2001. Mosquito surveillance for West Nile virus in Connecticut, 2000: isolation from *Culex pipiens*, *Cx. restuans*, *Cx. salinarius*, and *Culiseta melanura*. *Emerg. Infect. Dis.* 7: 670–674.
- Andreadis, T. G., J. F. Anderson, C. R. Vossbrinck, and A. J. Main. 2004. Epidemiology of West Nile virus in Connecticut: a five-year analysis of mosquito data 1999–2003. *Vector Borne Zoonotic Dis.* 4: 360–378.
- Andreadis, T. G., M. C. Thomas, J. Shepard, and J. J. Shephard. 2005. Identification guide to the mosquitoes of Connecticut. The Connecticut Agricultural Experimental Station, New Haven, CT.
- Andreadis, T. G., P. M. Armstrong, and W. I. Bajwa. 2010. Studies on hibernating populations of *Culex pipiens* from a West Nile virus endemic focus in New York City: parity rates and isolation of West Nile virus. *J. Am. Mosq. Control Assoc.* 26: 257–264.
- Apperson, C. S., B. A. Harrison, T. R. Unnasch, H. K. Hassan, W. S. Irby, H. M. Savage, S. E. Aspen, D. W. Watson, L. M. Rueda, B. R. Engber, et al. 2002. Host-feeding habits of *Culex* and other mosquitoes (Diptera: Culicidae) in the Borough of Queens in New York City, with characters and techniques for identification of *Culex* mosquitoes. *J. Med. Entomol.* 39: 777–785.
- Apperson, C. S., H. K. Hassan, B. A. Harrison, H. M. Savage, S. E. Aspen, A. Farajollahi, W. Crans, T. J. Daniels, R. C. Falco, M. Benedict, et al. 2004. Host feeding patterns of established and potential mosquito vectors of West Nile virus in the eastern United States. *Vector Borne Zoonotic Dis.* 4: 71–82.
- Bajwa, W. I. 2018. A taxonomic checklist and relative abundance of the mosquitoes of New York City. *J. Am. Mosq. Control Assoc.* 34: 138–142.
- Barker, C. M., B. F. Eldridge, and W. K. Reisen. 2010. Seasonal abundance of *Culex tarsalis* and *Culex pipiens* complex mosquitoes (Diptera: Culicidae) in California. *J. Med. Entomol.* 47: 759–768.
- Becker, B., P. T. Leisnham, and S. L. LaDeau. 2014. A tale of two city blocks: differences in immature and adult mosquito abundances between socio-economically different urban blocks in Baltimore (Maryland, USA). *Int. J. Environ. Res. Public Health* 11: 3256–3270.
- Bell, J. A., N. J. Mickelson, and J. A. Vaughan. 2005. West Nile virus in host-seeking mosquitoes within a residential neighborhood in Grand Forks, North Dakota. *Vector Borne Zoonotic Dis.* 5: 373–382.
- Bohart, R. M., and R. K. Washino. 1978. Mosquitoes of California. University of California Division of Agricultural Sciences, Berkeley, CA.
- Bolling, B. G., J. H. Kennedy, and E. G. Zimmerman. 2005. Seasonal dynamics of four potential West Nile vector species in north-central Texas. *J. Vector Ecol.* 30: 186–194.
- Bolling, B. G., C. G. Moore, S. L. Anderson, C. D. Blair, and B. J. Beaty. 2007. Entomological studies along the Colorado Front Range during a period of intense West Nile virus activity. *J. Am. Mosq. Control Assoc.* 23: 37–46.
- Bolling, B. G., C. M. Barker, C. G. Moore, W. J. Pape, and L. Eisen. 2009. 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.* 46: 1519–1531.
- Bowden, S. E., K. Magori, and J. M. Drake. 2011. Regional differences in the association between land cover and West Nile virus disease incidence in humans in the United States. *Am. J. Trop. Med. Hyg.* 84: 234–238.
- Bradford, C. M., W. Gellido, and S. M. Presley. 2008. Survey of mosquito fauna in Lubbock County, Texas. *J. Am. Mosq. Control Assoc.* 24: 453–456.
- Brady, O. J., M. A. Johansson, C. A. Guerra, S. Bhatt, N. Golding, D. M. Pigott, H. Delatte, M. G. Grech, P. T. Leisnham, R. Maciel-de-Freitas, et al. 2013. Modelling adult *Aedes aegypti* and *Aedes albopictus* survival at different temperatures in laboratory and field settings. *Parasit. Vectors.* 6: 351.
- Burkett-Cadena, N. D., R. A. Ligon, M. Liu, H. K. Hassan, G. E. Hill, M. D. Eubanks, and T. R. Unnasch. 2010. Vector-host interactions in avian nests: do mosquitoes prefer nestlings over adults? *Am. J. Trop. Med. Hyg.* 83: 395–399.
- Calhoun, L. M., M. Avery, L. Jones, K. Gunarto, R. King, J. Roberts, and T. R. Burkot. 2007. Combined sewage overflows (CSO) are major urban breeding sites for *Culex quinquefasciatus* in Atlanta, Georgia. *Am. J. Trop. Med. Hyg.* 77: 478–484.
- Campbell, R., T. C. Thiemann, D. Lemenager, and W. K. Reisen. 2013. Host-selection patterns of *Culex tarsalis* (Diptera: Culicidae) determine the spatial heterogeneity of West Nile virus enzootic activity in northern California. *J. Med. Entomol.* 50: 1303–1309.
- Chen, C. C., T. Epp, E. Jenkins, C. Waldner, P. S. Curry, and C. Soos. 2012. Predicting weekly variation of *Culex tarsalis* (Diptera: Culicidae) West Nile virus infection in a newly endemic region, the Canadian prairies. *J. Med. Entomol.* 49: 1144–1153.
- Chung, W. M., C. M. Buseman, S. N. Joyner, S. M. Hughes, T. B. Fomby, J. P. Luby, and R. W. Haley. 2013. The 2012 West Nile encephalitis epidemic in Dallas, Texas. *Jama.* 310: 297–307.
- Ciota, A. T., A. C. Matarachero, A. M. Kilpatrick, and L. D. Kramer. 2014. The effect of temperature on life history traits of *Culex* mosquitoes. *J. Med. Entomol.* 51: 55–62.
- Cohen, S. B., K. Lewoczko, D. B. Huddleston, E. Moody, S. Mukherjee, J. R. Dunn, T. F. Jones, R. Wilson, and A. C. Moncayo. 2009. Host feeding patterns of potential vectors of eastern equine encephalitis virus at an enzootic focus in Tennessee. *Am. J. Trop. Med. Hyg.* 81: 452–456.
- Colborn, J. M., K. A. Smith, J. Townsend, D. Damian, R. S. Nasci, and J. P. Mutebi. 2013. West Nile virus outbreak in Phoenix, Arizona—2010: entomological observations and epidemiological correlations. *J. Am. Mosq. Control Assoc.* 29: 123–132.
- Colpitts, T. M., M. J. Conway, R. R. Montgomery, and E. Fikrig. 2012. West Nile Virus: biology, transmission, and human infection. *Clin. Microbiol. Rev.* 25: 635–648.
- Cooke, W. H., III, K. Grala, and R. C. Wallis. 2006. Avian GIS models signal human risk for West Nile virus in Mississippi. *Int. J. Health Geogr.* 5: 36.
- Crans, W. J. 1964. Continued host preference studies with New Jersey mosquitoes, 1963. *Proc. New Jersey Mosq. Control Assoc.* 51: 50–58.
- Crowder, D. W., E. A. Dykstra, J. M. Brauner, A. Duffy, C. Reed, E. Martin, W. Peterson, Y. Carrière, P. Dutilleul, and J. P. Owen. 2013. West Nile virus prevalence across landscapes is mediated by local effects of agriculture on vector and host communities. *PLoS One* 8: e55006.
- Curry, P. 2004. Saskatchewan mosquitoes and West Nile virus. *Blue Jay.* 62: 104–111.
- Darsie, R. F., and R. A. Ward. 2005. Identification and geographical distribution of the mosquitoes of North America. University Press of Florida, Gainesville, FL.
- DeGroot, J. P., R. Sugumaran, S. M. Brend, B. J. Tucker, and L. C. Bartholomay. 2008. Landscape, demographic, entomological, and climatic associations with human disease incidence of West Nile virus in the state of Iowa, USA. *Int. J. Health Geogr.* 7: 19.
- DeGroot, J. P., R. Sugumaran, and M. Ecker. 2014. Landscape, demographic and climatic associations with human West Nile virus occurrence regionally in 2012 in the United States of America. *Geospat. Health.* 9: 153–168.
- Dennett, J. A., A. Bala, T. Wuthiranyagool, Y. Randle, C. B. Sargent, H. Guzman, M. Siirin, H. K. Hassan, M. Reyna-Nava, T. R. Unnasch, et al. 2007. Associations between two mosquito populations and West Nile virus in Harris County, Texas, 2003–06. *J. Am. Mosq. Control Assoc.* 23: 264–275.
- DiMenna, M. A., R. Bueno, Jr, R. R. Parmenter, D. E. Norris, J. M. Sheyka, J. L. Molina, E. M. LaBeau, E. S. Hatton, and G. E. Glass. 2006. Emergence of West Nile virus in mosquito (Diptera: Culicidae) communities of the New Mexico Rio Grande Valley. *J. Med. Entomol.* 43: 594–599.
- Dohm, D. J., M. L. O’Guinn, and M. J. Turell. 2002. Effect of environmental temperature on the ability of *Culex pipiens* (Diptera: Culicidae) to transmit West Nile virus. *J. Med. Entomol.* 39: 221–225.
- Dunphy, B. M., K. B. Kovach, E. J. Gehrke, E. N. Field, W. A. Rowley, L. C. Bartholomay, and R. C. Smith. 2019. Long-term surveillance defines

- spatial and temporal patterns implicating *Culex tarsalis* as the primary vector of West Nile virus. *Sci. Rep.* 9: 6637.
- Ebel, G. D., I. Rochlin, J. Longacker, and L. D. Kramer. 2005. *Culex restuans* (Diptera: Culicidae) relative abundance and vector competence for West Nile Virus. *J. Med. Entomol.* 42: 838–843.
- Edman, J. D. 1974. Host-feeding patterns of Florida mosquitoes. 3. *Culex* (*Culex*) and *Culex* (*Neoculex*). *J. Med. Entomol.* 11: 95–104.
- Egizi, A. M., A. Farajollahi, and D. M. Fonseca. 2014. Diverse host feeding on nesting birds may limit early-season West Nile virus amplification. *Vector Borne Zoonotic Dis.* 14: 447–453.
- Eldridge, B. F., C. L. Bailey, and M. D. Johnson. 1972. A preliminary study of the seasonal geographic distribution and overwintering of *Culex restuans* Theobald and *Culex salinarius* Coquillett (Diptera: Culicidae). *J. Med. Entomol.* 9: 233–238.
- Erickson, S. M., K. B. Platt, B. J. Tucker, R. Evans, S. Tiawirisup, and W. A. Rowley. 2006. The potential of *Aedes triseriatus* (Diptera: Culicidae) as an enzootic vector of West Nile virus. *J. Med. Entomol.* 43: 966–970.
- Ezenwa, V. O., M. S. Godsey, R. J. King, and S. C. Guptill. 2006. Avian diversity and West Nile virus: testing associations between biodiversity and infectious disease risk. *Proc. Biol. Sci.* 273: 109–117.
- Faraji, A., A. Egizi, D. M. Fonseca, I. Unlu, T. Crepeau, S. P. Healy, and R. Gaugler. 2014. Comparative host feeding patterns of the Asian tiger mosquito, *Aedes albopictus*, in urban and suburban Northeastern USA and implications for disease transmission. *Plos Negl. Trop. Dis.* 8: e3037.
- Faraji, A., and R. Gaugler. 2015. Experimental host preference of diapause and non-diapause induced *Culex pipiens pipiens* (Diptera: Culicidae). *Parasit. Vectors.* 8: 389.
- Farajollahi, A., W. J. Crans, P. Bryant, B. Wolf, K. L. Burkhalter, M. S. Godsey, S. E. Aspen, and R. S. Nasci. 2005. Detection of West Nile viral RNA from an overwintering pool of *Culex pipiens pipiens* (Diptera: Culicidae) in New Jersey, 2003. *J. Med. Entomol.* 42: 490–494.
- Farajollahi, A., D. M. Fonseca, L. D. Kramer, and A. Marm Kilpatrick. 2011. “Bird biting” mosquitoes and human disease: a review of the role of *Culex pipiens* complex mosquitoes in epidemiology. *Infect. Genet. Evol.* 11: 1577–1585.
- Fonseca, D. M., N. Keyghobadi, C. A. Malcolm, C. Mehmet, F. Schaffner, M. Mogi, R. C. Fleischer, and R. C. Wilkerson. 2004. Emerging vectors in the *Culex pipiens* complex. *Science.* 303: 1535–1538.
- Freier, J. E. 1989. Estimation of vectorial capacity: vector abundance in relation to man. *Bull. Soc. Vector Ecol.* 14: 41–46.
- Ganser, C., and S. M. Wisely. 2013. Patterns of spatio-temporal distribution, abundance, and diversity in a mosquito community from the eastern Smoky Hills of Kansas. *J. Vector Ecol.* 38: 229–236.
- Gardner, A. M., G. L. Hamer, A. M. Hines, C. M. Newman, E. D. Walker, and M. O. Ruiz. 2012. Weather variability affects abundance of larval *Culex* (Diptera: Culicidae) in storm water catch basins in suburban Chicago. *J. Med. Entomol.* 49: 270–276.
- Gardner, A. M., T. K. Anderson, G. L. Hamer, D. E. Johnson, K. E. Varela, E. D. Walker, and M. O. Ruiz. 2013. Terrestrial vegetation and aquatic chemistry influence larval mosquito abundance in catch basins, Chicago, USA. *Parasit. Vectors.* 6: 9.
- Geery, P. R., and R. E. Holub. 1989. Seasonal abundance and control of *Culex* spp. in catch basins in Illinois. *J. Am. Mosq. Control Assoc.* 5: 537–540.
- Gingrich, J. B., and G. M. Williams. 2005. Host-feeding patterns of suspected West Nile virus mosquito vectors in Delaware, 2001–2002. *J. Am. Mosq. Control Assoc.* 21: 194–200.
- Girard, Y. A., V. Popov, J. Wen, V. Han, and S. Higgs. 2006. Ultrastructural study of West Nile Virus pathogenesis in *Culex pipiens quinquefasciatus* (Diptera: Culicidae). *J. Med. Entomol.* 42: 429–444.
- Girard, Y. A., G. F. Mayhew, J. F. Fuchs, H. Li, B. S. Schneider, C. E. McGee, T. A. Rocheleau, H. Helmy, B. M. Christensen, S. Higgs, et al. 2010. Transcriptome changes in *Culex quinquefasciatus* (Diptera: Culicidae) salivary glands during West Nile virus infection. *J. Med. Entomol.* 47: 421–435.
- Goddard, L. B., A. E. Roth, W. K. Reisen, and T. W. Scott. 2002. Vector competence of California mosquitoes for West Nile virus. *Emerg. Infect. Dis.* 8: 1385–1391.
- Goddard, L., A. Roth, W. K. Reisen, and T. W. Scott. 2003. Extrinsic incubation period of West Nile virus in four California *Culex* (Diptera: Culicidae) species. *Proc. Mosq. Vector Control Assoc. Calif.* 71: 70–75.
- Godsey, M. S., Jr, M. S. Blackmore, N. A. Panella, K. Burkhalter, K. Gottfried, L. A. Halsey, R. Rutledge, S. A. Langevin, R. Gates, K. M. Lamonte, et al. 2005. West Nile virus epizootiology in the southeastern United States, 2001. *Vector Borne Zoonotic Dis.* 5: 82–89.
- Godsey, M. S., Jr, K. Burkhalter, G. Young, M. Delorey, K. Smith, J. Townsend, C. Levy, and J. P. Mutebi. 2012. Entomologic investigations during an outbreak of West Nile virus disease in Maricopa County, Arizona, 2010. *Am. J. Trop. Med. Hyg.* 87: 1125–1131.
- Godsey, M. S., Jr, R. J. King, K. Burkhalter, M. Delorey, L. Colton, D. Charnetzky, G. Sutherland, V. O. Ezenwa, L. A. Wilson, M. Coffey, et al. 2013. Ecology of potential West Nile virus vectors in Southeastern Louisiana: enzootic transmission in the relative absence of *Culex quinquefasciatus*. *Am. J. Trop. Med. Hyg.* 88: 986–996.
- Hamer, G. L., U. D. Kitron, J. D. Brawn, S. R. Loss, M. O. Ruiz, T. L. Goldberg, and E. D. Walker. 2008. *Culex pipiens* (Diptera: Culicidae): a bridge vector of West Nile virus to humans. *J. Med. Entomol.* 45: 125–128.
- Hamer, G. L., U. D. Kitron, T. L. Goldberg, J. D. Brawn, S. R. Loss, M. O. Ruiz, D. B. Hayes, and E. D. Walker. 2009. Host selection by *Culex pipiens* mosquitoes and West Nile virus amplification. *Am. J. Trop. Med. Hyg.* 80: 268–278.
- Haramis, L. D., and W. A. Foster. 1983. Survival and population density of *Aedes triseriatus* (Diptera: Culicidae) in a woodlot in central Ohio, USA. *J. Med. Entomol.* 20: 391–398.
- Hardy, J. L., E. J. Houk, L. D. Kramer, and W. C. Reeves. 1983. Intrinsic factors affecting vector competence of mosquitoes for arboviruses. *Annu. Rev. Entomol.* 28: 229–262.
- Harrington, L. C., and R. L. Poulson. 2008. Considerations for accurate identification of adult *Culex restuans* (Diptera: Culicidae) in field studies. *J. Med. Entomol.* 45: 1–8.
- Harrison, B. A., P. B. Whitt, L. F. Roberts, J. A. Lehman, N. P. Lindsey, R. S. Nasci, and G. R. Hansen. 2009. Rapid assessment of mosquitoes and arbovirus activity after floods in southeastern Kansas, 2007. *J. Am. Mosq. Control Assoc.* 25: 265–271.
- Hassan, H. K., E. W. Cupp, G. E. Hill, C. R. Katholi, K. Klingler, and T. R. Unnasch. 2003. Avian host preference by vectors of eastern equine encephalomyelitis virus. *Am. J. Trop. Med. Hyg.* 69: 641–647.
- Hayes, R. O. 1961. Host preferences of *Caliseta melanura* and allied mosquitoes. *Mosq. News.* 21: 179–187.
- Helbing, C. M., D. L. Moorhead, and L. Mitchell. 2015. Population dynamics of *Culex restuans* and *Culex pipiens* (Diptera: Culicidae) Related to Climatic Factors in Northwest Ohio. *Environ. Entomol.* 44: 1022–1028.
- Huang, S., G. Molaei, and T. G. Andreadis. 2008. Genetic insights into the population structure of *Culex pipiens* (Diptera: Culicidae) in the Northeastern United States by using microsatellite analysis. *Am. J. Trop. Med. Hyg.* 79: 518–527.
- Huang, S., G. L. Hamer, G. Molaei, E. D. Walker, T. L. Goldberg, U. D. Kitron, and T. G. Andreadis. 2009. Genetic variation associated with mammalian feeding in *Culex pipiens* from a West Nile virus epidemic region in Chicago, Illinois. *Vector Borne Zoonotic Dis.* 9: 637–642.
- Irwin, P., C. Arcari, J. Hausbeck, and S. Paskewitz. 2008. Urban wet environment as mosquito habitat in the upper midwest. *Ecohealth.* 5: 49–57.
- Jackson, B. T., and S. L. Paulson. 2006. Seasonal abundance of *Culex restuans* and *Culex pipiens* in southwestern Virginia through ovitrapping. *J. Am. Mosq. Control Assoc.* 22: 206–212.
- Jacobson, E. R., P. E. Ginn, J. M. Troutman, L. Farina, L. Stark, K. Klenk, K. L. Burkhalter, and N. Komar. 2005. West Nile virus infection in farmed American alligators (*Alligator mississippiensis*) in Florida. *J. Wildl. Dis.* 41: 96–106.
- Jenkins, D. W. 1950. Bionomics of *Culex tarsalis* in relation to Western equine encephalomyelitis. *Am. J. Trop. Med. Hyg.* 30: 909–916.
- Jensen, T., and R. K. Washino. 1994. Comparison of recapture patterns of marked and released *Aedes vexans* and *Ae. melanimon* (Diptera: Culicidae) in the Sacramento Valley of California. *J. Med. Entomol.* 31: 607–610.

- Johnson, B. J., and M. V. Sukhdeo. 2013. Drought-induced amplification of local and regional West Nile virus infection rates in New Jersey. *J. Med. Entomol.* 50: 195–204.
- Johnson, B. J., M. G. Robson, and D. M. Fonseca. 2015. Unexpected spatio-temporal abundance of infected *Culex restuans* suggest a greater role as a West Nile virus vector for this native species. *Infect. Genet. Evol.* 31: 40–47.
- Jones, C. E., L. P. Lounibos, P. P. Marra, and A. M. Kilpatrick. 2012. Rainfall influences survival of *Culex pipiens* (Diptera: Culicidae) in a residential neighborhood in the mid-Atlantic United States. *J. Med. Entomol.* 49: 467–473.
- Kaufman, M. G., and D. M. Fonseca. 2014. Invasion biology of *Aedes japonicus japonicus* (Diptera: Culicidae). *Annu. Rev. Entomol.* 59: 31–49.
- Kaufman, P. E., L. C. Harrington, J. K. Waldron, and D. A. Rutz. 2005. The importance of agricultural tire habitats for mosquitoes of public health importance in New York State. *J. Am. Mosq. Control Assoc.* 21: 171–176.
- Kent, R. J. 2009. Molecular methods for arthropod bloodmeal identification and applications to ecological and vector-borne disease studies. *Mol. Ecol. Resour.* 9: 4–18.
- Kent, R. J., L. C. Harrington, and D. E. Norris. 2007. Genetic differences between *Culex pipiens f. molestus* and *Culex pipiens pipiens* (Diptera: Culicidae) in New York. *J. Med. Entomol.* 44: 50–59.
- Kent, R., L. Juliusson, M. Weissmann, S. Evans, and N. Komar. 2009. Seasonal blood-feeding behavior of *Culex tarsalis* (Diptera: Culicidae) in Weld County, Colorado, 2007. *J. Med. Entomol.* 46: 380–390.
- Kilpatrick, A. M., L. D. Kramer, S. R. Campbell, E. O. Alleyne, A. P. Dobson, and P. Daszak. 2005. West Nile virus risk assessment and the bridge vector paradigm. *Emerg. Infect. Dis.* 11: 425–429.
- Kilpatrick, A. M., L. D. Kramer, M. J. Jones, P. P. Marra, and P. Daszak. 2006a. West Nile virus epidemics in North America are driven by shifts in mosquito feeding behavior. *PLoS Biol.* 4: 606–610.
- Kilpatrick, A. M., P. Daszak, M. J. Jones, P. P. Marra, and L. D. Kramer. 2006b. Host heterogeneity dominates West Nile virus transmission. *Proc. Biol. Sci.* 273: 2327–2333.
- Kilpatrick, A. M., L. D. Kramer, M. J. Jones, P. P. Marra, P. Daszak, and D. M. Fonseca. 2007. Genetic influences on mosquito feeding behavior and the emergence of zoonotic pathogens. *Am. J. Trop. Med. Hyg.* 77: 667–671.
- Kilpatrick, A. M., M. A. Meola, R. M. Moudy, and L. D. Kramer. 2008. Temperature, viral genetics, and the transmission of West Nile virus by *Culex pipiens* mosquitoes. *PLoS Pathog.* 4: e1000092.
- Kilpatrick, A. M., D. M. Fonseca, G. D. Ebel, M. R. Reddy, and L. D. Kramer. 2010. Spatial and temporal variation in vector competence of *Culex pipiens* and *Cx. restuans* mosquitoes for West Nile virus. *Am. J. Trop. Med. Hyg.* 83: 607–613.
- Klenk, K., J. Snow, K. Morgan, R. Bowen, M. Stephens, F. Foster, P. Gordy, S. Beckett, N. Komar, D. Gubler, and M. Bunning. 2004. Alligators as West Nile virus amplifiers. *Emerg. Infect. Dis.* 10: 2150–2155.
- Komar, N. 2003. West Nile virus: epidemiology and ecology in North America. *Adv. Virus Res.* 61: 185–234.
- Komar, N., S. Langevin, S. Hinten, N. Nemeth, E. Edwards, D. Hettler, B. Davis, R. Bowen, and M. Bunning. 2003. Experimental infection of North American birds with the New York 1999 strain of West Nile virus. *Emerg. Infect. Dis.* 9: 311–322.
- Kothera, L., E. M. Zimmerman, C. M. Richards, and H. M. Savage. 2009. Microsatellite characterization of subspecies and their hybrids in *Culex pipiens* complex (Diptera: Culicidae) mosquitoes along a north-south transect in the central United States. *J. Med. Entomol.* 46: 236–248.
- Kothera, L., M. Godsey, J. P. Mutebi, and H. M. Savage. 2010. A comparison of aboveground and belowground populations of *Culex pipiens* (Diptera: Culicidae) mosquitoes in Chicago, Illinois, and New York City, New York, using microsatellites. *J. Med. Entomol.* 47: 805–813.
- Kothera, L., B. M. Nelms, W. K. Reisen, and H. M. Savage. 2013. Population genetic and admixture analyses of *Culex pipiens* complex (Diptera: Culicidae) populations in California, United States. *Am. J. Trop. Med. Hyg.* 89: 1154–1167.
- Kramer, L. D., L. M. Styer, and G. D. Ebel. 2008. A global perspective on the epidemiology of West Nile virus. *Annu. Rev. Entomol.* 53: 61–81.
- Kulasekera, V. L., L. Kramer, R. S. Nasci, F. Mostashari, B. Cherry, S. C. Trock, C. Glaser, and J. R. Miller. 2001. West Nile virus infection in mosquitoes, birds, horses, and humans, Staten Island, New York, 2000. *Emerg. Infect. Dis.* 7: 722–725.
- Kunkel, K. E., R. J. Novak, R. L. Lampman, and W. Gu. 2006. Modeling the impact of variable climatic factors on the crossover of *Culex restuans* and *Culex pipiens* (Diptera: culicidae), vectors of West Nile virus in Illinois. *Am. J. Trop. Med. Hyg.* 74: 168–173.
- Kwan, J. L., S. Klueh, M. B. Madon, and W. K. Reisen. 2010. West Nile virus emergence and persistence in Los Angeles, California, 2003–2008. *Am. J. Trop. Med. Hyg.* 83: 400–412.
- Kwan, J. L., B. K. Park, T. E. Carpenter, V. Ngo, R. Civen, and W. K. Reisen. 2012. Comparison of enzootic risk measures for predicting West Nile disease, Los Angeles, California, USA, 2004–2010. *Emerg. Infect. Dis.* 18: 1298–1306.
- Lampman, R., M. Slamecka, N. Krasavin, K. Kunkel, and R. Novak. 2006. *Culex* population dynamics and West Nile virus transmission in east-central Illinois. *J. Am. Mosq. Control Assoc.* 22: 390–400.
- Levine, R. S., D. G. Mead, G. L. Hamer, B. J. Brosi, D. L. Hedeem, M. W. Hedeem, J. R. McMillan, D. Bisanzio, and U. D. Kitron. 2016. Supersuppression: reservoir competency and timing of mosquito host shifts combine to reduce spillover of West Nile Virus. *Am. J. Trop. Med. Hyg.* 95: 1174–1184.
- Levine, R. S., D. L. Hedeem, M. W. Hedeem, G. L. Hamer, D. G. Mead, and U. D. Kitron. 2017. Avian species diversity and transmission of West Nile virus in Atlanta, Georgia. *Parasit. Vectors.* 10: 62.
- Ligon, R. A., N. D. Burkett-Cadena, M. Liu, G. E. Hill, H. K. Hassan, and T. R. Unnasch. 2009. Assessing mosquito feeding patterns on nestling and brooding adult birds using microsatellite markers. *Am. J. Trop. Med. Hyg.* 81: 534–537.
- Lujan, D. A., J. A. Greenberg, A. S. Hung, M. A. Dimenna, and B. V. Hofkin. 2014. Evaluation of seasonal feeding patterns of West Nile virus vectors in Bernalillo county, New Mexico, United States: implications for disease transmission. *J. Med. Entomol.* 51: 264–268.
- Lukacik, G., M. Anand, E. J. Shusas, J. J. Howard, J. Oliver, H. Chen, P. B. Backenson, E. B. Kauffman, K. A. Bernard, L. D. Kramer, et al. 2006. West Nile virus surveillance in mosquitoes in New York State, 2000–2004. *J. Am. Mosq. Control Assoc.* 22: 264–271.
- Mackay, A. J., W. L. Kramer, J. K. Meece, R. T. Brumfield, and L. D. Foil. 2010. Host feeding patterns of *Culex* mosquitoes (Diptera: Culicidae) in East Baton Rouge Parish, Louisiana. *J. Med. Entomol.* 47: 238–248.
- Mattingly, P. F., L. E. Rozeboom, K. L. Knight, H. Laven, F. H. Drummond, S. R. Christophers, and P. G. Shute. 1951. The *Culex pipiens* complex. *Trans. R. Entomol. Soc. London.* 102: 331–342.
- McNeel, T. E., and F. E. Ferguson. 1954. Mosquito distribution and abundance in the Arkansas-White-Red River Basins. *Public Health Rep.* 69: 385–390.
- Means, R. G. 1968. Host preferences of mosquitoes (Diptera: culicidae) in Suffolk County, New York. *Ann. Entomol. Soc. Am.* 61: 116–119.
- Means, R. G. 1987. Mosquitoes of New York. Part II. Genera of Culicidae other than *Aedes* occurring in New York. *New York State Mus. Bull.* 430b: 1–180.
- Metzger, M. E., C. M. Myers, S. Klueh, J. W. Wekesa, R. Hu, and V. L. Kramer. 2008. An assessment of mosquito production and nonchemical control measures in structural stormwater best management practices in southern California. *J. Am. Mosq. Control Assoc.* 24: 70–81.
- Meuti, M. E., C. A. Short, and D. L. Denlinger. 2015. Mom Matters: Diapause Characteristics of *Culex pipiens-Culex quinquefasciatus* (Diptera: Culicidae) Hybrid Mosquitoes. *J. Med. Entomol.* 52: 131–137.
- Moise, I. K., C. Riegel, and E. J. Muturi. 2018. Environmental and social-demographic predictors of the southern house mosquito *Culex quinquefasciatus* in New Orleans, Louisiana. *Parasit. Vectors.* 11: 249.
- Molaei, G., and T. G. Andreadis. 2006. Identification of avian- and mammalian-derived bloodmeals in *Aedes vexans* and *Culiseta melanura* (Diptera: Culicidae) and its implication for West Nile virus transmission in Connecticut, U.S.A. *J. Med. Entomol.* 43: 1088–1093.
- Molaei, G., T. G. Andreadis, P. M. Armstrong, J. F. Anderson, and C. R. Vossbrinck. 2006. Host feeding patterns of *Culex* mosquitoes and West Nile virus transmission, northeastern United States. *Emerg. Infect. Dis.* 12: 468–474.

- Molaei, G., T. G. Andreadis, P. M. Armstrong, R. Bueno, Jr, J. A. Dennett, S. V. Real, C. Sargent, A. Bala, Y. Randle, H. Guzman, et al. 2007. Host feeding pattern of *Culex quinquefasciatus* (Diptera: Culicidae) and its role in transmission of West Nile virus in Harris County, Texas. *Am. J. Trop. Med. Hyg.* 77: 73–81.
- Molaei, G., T. G. Andreadis, P. M. Armstrong, and M. Diuk-Wasser. 2008. Host-feeding patterns of potential mosquito vectors in Connecticut, U.S.A.: molecular analysis of bloodmeals from 23 species of *Aedes*, *Anopheles*, *Culex*, *Coquillettidia*, *Psorophora*, and *Uranotaenia*. *J. Med. Entomol.* 45: 1143–1151.
- Molaei, G., A. Farajollahi, J. J. Scott, R. Gaugler, and T. G. Andreadis. 2009. Human bloodfeeding by the recently introduced mosquito, *Aedes japonicus japonicus*, and public health implications. *J. Am. Mosq. Control Assoc.* 25: 210–214.
- Molaei, G., R. F. Cummings, T. Su, P. M. Armstrong, G. A. Williams, M. L. Cheng, J. P. Webb, and T. G. Andreadis. 2010. Vector-host interactions governing epidemiology of West Nile virus in Southern California. *Am. J. Trop. Med. Hyg.* 83: 1269–1282.
- Montgomery, M. J., T. Thiemann, P. Macedo, D. A. Brown, and T. W. Scott. 2011. Blood-feeding patterns of the *Culex pipiens* complex in Sacramento and Yolo Counties, California. *J. Med. Entomol.* 48: 398–404.
- Mutebi, J. P., B. N. Swope, M. S. Doyle, and B. J. Biggerstaff. 2012. Vector competence of *Culex restuans* (Diptera: Culicidae) from two regions of Chicago with low and high prevalence of West Nile virus human infections. *J. Med. Entomol.* 49: 678–686.
- Nasci, R. S., H. M. Savage, D. J. White, J. R. Miller, B. C. Cropp, M. S. Godsey, A. J. Kerst, P. Bennett, K. Gottfried, and R. S. Lanciotti. 2001. West Nile virus in overwintering *Culex* mosquitoes, New York City, 2000. *Emerg. Infect. Dis.* 7: 742–744.
- Nayar, J. K., L. Rosen, and J. W. Knight. 1986. Experimental vertical transmission of Saint Louis encephalitis virus by Florida mosquitoes. *Am. J. Trop. Med. Hyg.* 35: 1296–1301.
- Nelms, B. M., L. Kothera, T. Thiemann, P. A. Macedo, H. M. Savage, and W. K. Reisen. 2013. Phenotypic variation among *Culex pipiens* complex (Diptera: Culicidae) populations from the Sacramento Valley, California: horizontal and vertical transmission of West Nile virus, diapause potential, autogeny, and host selection. *Am. J. Trop. Med. Hyg.* 89: 1168–1178.
- Nelson, R. L., M. M. Milby, W. C. Reeves, and P. E. M. Fine. 1978. Estimates of survival, population size, and emergence of *Culex tarsalis* at an isolated site. *Ann. Entomol. Soc. Am.* 71: 801–808.
- Niebylski, M. L., and G. B. Craig, Jr. 1994. Dispersal and survival of *Aedes albopictus* at a scrap tire yard in Missouri. *J. Am. Mosq. Control Assoc.* 10: 339–343.
- Niebylski, M. L., H. M. Savage, R. S. Nasci, and G. B. Craig, Jr. 1994. Blood hosts of *Aedes albopictus* in the United States. *J. Am. Mosq. Control Assoc.* 10: 447–450.
- Noden, B. H., L. Coburn, R. Wright, and K. Bradley. 2015. An updated checklist of the mosquitoes of Oklahoma including new state records and west Nile virus vectors, 2003–06. *J. Am. Mosq. Control Assoc.* 31: 336–345.
- Nolan, M. S., J. Schuermann, and K. O. Murray. 2013. West Nile virus infection among humans, Texas, USA, 2002–2011. *Emerg. Infect. Dis.* 19: 137–139.
- Pitzer, J. B., R. L. Byford, H. B. Vuong, R. L. Steiner, R. J. Creamer, and D. F. Caccamise. 2009. Potential vectors of West Nile virus in a semi-arid environment: Doña Ana County, New Mexico. *J. Med. Entomol.* 46: 1474–1482.
- Reeves, L. E., K. L. Krysko, M. L. Avery, J. L. Gillett-Kaufman, A. Y. Kawahara, C. R. Connelly, and P. E. Kaufman. 2018. Interactions between the invasive Burmese python, *Python bivittatus* Kuhl, and the local mosquito community in Florida, USA. *PLoS One* 13: e0190633.
- Reisen, W. K. 1989. Relationship to disease transmission by malaria and arbovirus Vectors. *Bull. Soc. Vector Ecol.* 14: 67–70.
- Reisen, W. K. 2010. Landscape epidemiology of vector-borne diseases. *Annu. Rev. Entomol.* 55: 461–483.
- Reisen, W. K. 2012. The contrasting bionomics of *Culex* mosquitoes in western North America. *J. Am. Mosq. Control Assoc.* 28: 82–91.
- Reisen, W., and A. C. Brault. 2007. West Nile virus in North America: perspectives on epidemiology and intervention. *Pest Manag. Sci.* 63: 641–646.
- Reisen, W. K., R. P. Meyer, C. H. Tempelis, and J. J. Spoehel. 1990. Mosquito abundance and bionomics in residential communities in Orange and Los Angeles Counties, California. *J. Med. Entomol.* 27: 356–367.
- Reisen, W. K., M. M. Milby, and R. P. Meyer. 1992. Population dynamics of adult *Culex* mosquitoes (Diptera: Culicidae) along the Kern River, Kern County, California, in 1990. *J. Med. Entomol.* 29: 531–543.
- Reisen, W. K., H. D. Lothrop, and J. L. Hardy. 1995. Bionomics of *Culex tarsalis* (Diptera: Culicidae) in relation to arbovirus transmission in south-eastern California. *J. Med. Entomol.* 32: 316–327.
- Reisen, W., H. Lothrop, R. Chiles, M. Madon, C. Cossen, L. Woods, S. Husted, V. Kramer, and J. Edman. 2004. West Nile virus in California. *Emerg. Infect. Dis.* 10: 1369–1378.
- Reisen, W. K., Y. Fang, and V. M. Martinez. 2006. Effects of temperature on the transmission of west Nile virus by *Culex tarsalis* (Diptera: Culicidae). *J. Med. Entomol.* 43: 309–317.
- Reisen, W. K., R. M. Takahashi, B. D. Carroll, and R. Quiring. 2008a. Delinquent mortgages, neglected swimming pools, and West Nile virus, California. *Emerg. Infect. Dis.* 14: 1747–1749.
- Reisen, W. K., C. M. Barker, Y. Fang, and V. M. Martinez. 2008b. Does variation in *Culex* (Diptera: Culicidae) vector competence enable outbreaks of West Nile virus in California? *J. Med. Entomol.* 45: 1126–1138.
- Reisen, W. K., B. D. Carroll, R. Takahashi, Y. Fang, S. Garcia, V. M. Martinez, and R. Quiring. 2009. Repeated West Nile virus epidemic transmission in Kern County, California, 2004–2007. *J. Med. Entomol.* 46: 139–157.
- Rey, J. R., N. Nishimura, B. Wagner, M. A. Braks, S. M. O’Connell, and L. P. Lounibos. 2006. Habitat segregation of mosquito arbovirus vectors in south Florida. *J. Med. Entomol.* 43: 1134–1141.
- Richards, S. L., L. Ponnusamy, T. R. Unnasch, H. K. Hassan, and C. S. Apperson. 2006. Host-feeding patterns of *Aedes albopictus* (Diptera: Culicidae) in relation to availability of human and domestic animals in suburban landscapes of central North Carolina. *J. Med. Entomol.* 43: 543–551.
- Richards, S. L., S. L. Anderson, C. C. Lord, and W. J. Tabachnick. 2011. Impact of West Nile virus dose and incubation period on vector competence of *Culex nigripalpus* (Diptera: Culicidae). *Vector Borne Zoonotic Dis.* 11: 1487–1491.
- Ritchie, S. A., and W. A. Rowley. 1981. Blood-feeding patterns of Iowa mosquitoes. *Mosq. News.* 41: 271–275.
- Robertson, S. L., and K. A. Caillouët. 2016. A host stage-structured model of enzootic West Nile virus transmission to explore the effect of avian stage-dependent exposure to vectors. *J. Theor. Biol.* 399: 33–42.
- Rochlin, I., M. E. Dempsey, S. R. Campbell, and D. V. Ninivaggi. 2008a. Salt marsh as *Culex salinarius* larval habitat in coastal New York. *J. Am. Mosq. Control Assoc.* 24: 359–367.
- Rochlin, I., K. Harding, H. S. Ginsberg, and S. R. Campbell. 2008b. Comparative analysis of distribution and abundance of West Nile and eastern equine encephalomyelitis virus vectors in Suffolk County, New York, using human population density and land use/cover data. *J. Med. Entomol.* 45: 563–571.
- Rochlin, I., H. S. Ginsberg, and S. R. Campbell. 2009. Distribution and abundance of host-seeking *Culex* species at three proximate locations with different levels of West Nile virus activity. *Am. J. Trop. Med. Hyg.* 80: 661–668.
- Rochlin, I., R. Gaugler, E. Williges, and A. Farajollahi. 2013. The rise of the invasives and decline of the natives: insights revealed from adult populations of container-inhabiting *Aedes* mosquitoes (Diptera: Culicidae) in temperate North America. *Biol. Invasions.* 15: 991–1003.
- Rochlin, I., M. Kawalkowski, and D. V. Ninivaggi. 2016. Comparison of Mosquito magnet and biogenetics sentinel traps for operational surveillance of Container-Inhabiting *Aedes* (Diptera: Culicidae) Species. *J. Med. Entomol.* 53: 454–459.
- Roth, D., B. Henry, S. Mak, M. Fraser, M. Taylor, M. Li, K. Cooper, A. Furnell, Q. Wong, and M. Morshed; Members of the British Columbia West Nile Virus Surveillance Team. 2010. West Nile virus range expansion into British Columbia. *Emerg. Infect. Dis.* 16: 1251–1258.
- Ruiz, M. O., L. F. Chaves, G. L. Hamer, T. Sun, W. M. Brown, E. D. Walker, L. Haramis, T. L. Goldberg, and U. D. Kitron. 2010. Local impact of

- temperature and precipitation on West Nile virus infection in *Culex* species mosquitoes in northeast Illinois, USA. *Parasit. Vectors.* 3: 19.
- Ruybal, J. E., L. D. Kramer, and A. M. Kilpatrick. 2016. Geographic variation in the response of *Culex pipiens* life history traits to temperature. *Parasit. Vectors.* 9: 116.
- Sallam, M. F., R. D. Xue, R. M. Pereira, and P. G. Koehler. 2016. Ecological niche modeling of mosquito vectors of West Nile virus in St. John's County, Florida, USA. *Parasit. Vectors.* 9: 371.
- Sardelis, M. R., M. J. Turell, D. J. Dohm, and M. L. O'Guinn. 2001. Vector competence of selected North American *Culex* and *Coquillettidia* mosquitoes for West Nile virus. *Emerg. Infect. Dis.* 7: 1018–1022.
- Sardelis, M. R., M. J. Turell, M. L. O'Guinn, R. G. Andre, and D. R. Roberts. 2002. Vector competence of three North American strains of *Aedes albopictus* for West Nile virus. *J. Am. Mosq. Control Assoc.* 18: 284–289.
- Savage, H. M., M. L. Niebylski, G. C. Smith, C. J. Mitchell, and G. B. Craig, Jr. 1993. Host-feeding patterns of *Aedes albopictus* (Diptera: Culicidae) at a temperate North American site. *J. Med. Entomol.* 30: 27–34.
- Savage, H. M., D. Aggarwal, C. S. Apperson, C. R. Katholi, E. Gordon, H. K. Hassan, M. Anderson, D. Charnetzky, L. McMillen, E. A. Unnasch, et al. 2007. Host choice and West Nile virus infection rates in blood-fed mosquitoes, including members of the *Culex pipiens* complex, from Memphis and Shelby County, Tennessee, 2002–2003. *Vector Borne Zoonotic Dis.* 7: 365–386.
- Schönenberger, A. C., S. Wagner, H. C. Tuten, F. Schaffner, P. Torgerson, S. Furrer, A. Mathis, and C. Silaghi. 2016. Host preferences in host-seeking and blood-fed mosquitoes in Switzerland. *Med. Vet. Entomol.* 30: 39–52.
- Shaman, J., J. F. Day, and M. Stieglitz. 2005. Drought-induced amplification and epidemic transmission of West Nile virus in southern Florida. *J. Med. Entomol.* 42: 134–141.
- Shand, L., W. M. Brown, L. F. Chaves, T. L. Goldberg, G. L. Hamer, L. Haramis, U. Kitron, E. D. Walker, and M. O. Ruiz. 2016. Predicting West Nile virus infection risk from the synergistic effects of rainfall and temperature. *J. Med. Entomol.* 53: 935–944.
- Spielman, A. 1967. Population structure in the *Culex pipiens* complex of mosquitoes. *Bull. World Health Organ.* 37: 271–276.
- Strickman, D. A., and J. T. Lang. 1986. Activity of *Culex quinquefasciatus* in an underground storm drain in San Antonio, Texas. *J. Am. Mosq. Control Assoc.* 2: 379–381.
- Strickman, D., and D. M. Fonseca. 2012. Autogeny in *Culex pipiens* complex mosquitoes from the San Francisco Bay Area. *Am. J. Trop. Med. Hyg.* 87: 719–726.
- Su, T., J. P. Webb, R. P. Meyer, and M. S. Mulla. 2003. Spatial and temporal distribution of mosquitoes in underground storm drain systems in Orange County, California. *J. Vector Ecol.* 28: 79–89.
- Tempelis, C. H., W. C. Reeves, R. E. Bellamy, and M. F. Lofy. 1965. A three-year study of the feeding habits of *Culex tarsalis* in Kern County, California. *Am. J. Trop. Med. Hyg.* 14: 170–177.
- Tempelis, C. H., D. B. Francy, R. O. Hayes, and M. F. Lofy. 1967. Variations in feeding patterns of seven culicine mosquitoes on vertebrate hosts in Weld and Larimer Counties, Colorado. *Am. J. Trop. Med. Hyg.* 16: 111–119.
- Thiemann, T. C., S. S. Wheeler, C. M. Barker, and W. K. Reisen. 2011. Mosquito host selection varies seasonally with host availability and mosquito density. *Plos Negl. Trop. Dis.* 5: e1452.
- Thiemann, T. C., D. A. Lemenager, S. Klueh, B. D. Carroll, H. D. Lothrop, and W. K. Reisen. 2012. Spatial variation in host feeding patterns of *Culex tarsalis* and the *Culex pipiens* complex (Diptera: Culicidae) in California. *J. Med. Entomol.* 49: 903–916.
- Tiawsirisup, S., K. B. Platt, R. B. Evans, and W. A. Rowley. 2005. A comparison of West Nile Virus transmission by *Ochlerotatus trivittatus* (COQ.), *Culex pipiens* (L.), and *Aedes albopictus* (Skuse). *Vector Borne Zoonotic Dis.* 5: 40–47.
- Tiawsirisup, S., J. R. Kinley, B. J. Tucker, R. B. Evans, W. A. Rowley, and K. B. Platt. 2008. Vector competence of *Aedes vexans* (Diptera: Culicidae) for West Nile virus and potential as an enzootic vector. *J. Med. Entomol.* 45: 452–457.
- Tokarz, R. E., and R. C. Smith. 2019. Crossover dynamics of *Culex* (Diptera: Culicidae) vector populations determine WNV transmission intensity. *J. Med. Entomol.*
- Turell, M. J., M. L. O'Guinn, D. J. Dohm, and J. W. Jones. 2001. Vector competence of North American mosquitoes (Diptera: Culicidae) for West Nile virus. *J. Med. Entomol.* 38: 130–134.
- Turell, M. J., M. R. Sardelis, M. L. O'Guinn, and D. J. Dohm. 2002a. Potential vectors of West Nile virus in North America. *Curr. Top. Microbiol. Immunol.* 267: 241–252.
- Turell, M. J., M. L. O'Guinn, D. J. Dohm, J. P. Webb, Jr, and M. R. Sardelis. 2002b. Vector competence of *Culex tarsalis* from Orange County, California, for West Nile virus. *Vector Borne Zoonotic Dis.* 2: 193–196.
- Turell, M. J., D. J. Dohm, M. R. Sardelis, M. L. Oguinn, T. G. Andreadis, and J. A. Blow. 2005. An update on the potential of north American mosquitoes (Diptera: Culicidae) to transmit West Nile Virus. *J. Med. Entomol.* 42: 57–62.
- Unlu, I., A. J. Mackay, A. Roy, M. M. Yates, and L. D. Foil. 2010a. Evidence of vertical transmission of West Nile virus in field-collected mosquitoes. *J. Vector Ecol.* 35: 95–99.
- Unlu, I., W. L. Kramer, A. F. Roy, and L. D. Foil. 2010b. Detection of West Nile virus RNA in mosquitoes and identification of mosquito blood meals collected at alligator farms in Louisiana. *J. Med. Entomol.* 47: 625–633.
- Verna, T. N. 2015. Species composition and seasonal distribution of mosquito larvae (Diptera: Culicidae) in Southern New Jersey, Burlington County. *J. Med. Entomol.* 52: 1165–1169.
- Vitek, C. J., S. L. Richards, C. N. Mores, J. F. Day, and C. C. Lord. 2008. Arbovirus transmission by *Culex nigripalpus* in Florida, 2005. *J. Med. Entomol.* 45: 483–493.
- Walker, E. D., R. S. Copeland, S. L. Paulson, and L. E. Munstermann. 1987. Adult survivorship, population density, and body size in sympatric populations of *Aedes triseriatus* and *Aedes hendersoni* (Diptera: Culicidae). *J. Med. Entomol.* 24: 485–493.
- Williams, V. G., and C. T. Palmisano. 1981. Field-tests of methoprene (Altosid SR-10) and an experimental wettable powder (ZPA-1019) against *Culex quinquefasciatus* in septic ditches. *Mosq. News.* 41: 51–54.
- Winters, A. M., B. G. Bolling, B. J. Beaty, C. D. Blair, R. J. Eisen, A. M. Meyer, W. J. Pape, C. G. Moore, and L. Eisen. 2008. Combining mosquito vector and human disease data for improved assessment of spatial West Nile virus disease risk. *Am. J. Trop. Med. Hyg.* 78: 654–665.