

Effects of the El Niño - Southern Oscillation (ENSO) cycle on mosquito populations in southern California

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ABSTRACT: The abundance and species composition of adult mosquitoes collected by carbon dioxide-baited suction traps and gravid traps in western Los Angeles County, CA, were compared before and during a strong El Niño – Southern Oscillation (ENSO) cycle from December 1996 until November 1999. Following El Niño conditions in the winter 1997-1998, adult host-seeking mosquito abundance during spring was twice that observed during spring 1997 and species composition favored cool-weather mosquitoes such as *Culiseta incidens* and *Culex tarsalis*. The comparatively cool temperatures from early April until early June and increased rainfall of the 1998 El Niño negatively affected warm-weather mosquitoes such as *Culex quinquefasciatus* that inhabit eutrophic habitats such as urban storm drains. Gravid mosquito abundance during the early summer following El Niño conditions also increased 2- to 3-fold relative to 1997, but gravid mosquito species composition was not significantly affected by ENSO cycles, reflecting an inherent bias of gravid traps to collect predominantly *Cx. quinquefasciatus*. Relative to spring 1997, host-seeking and gravid mosquito abundances were reduced 3- to 7-fold from March until June 1999 under the comparatively dry La Niña conditions. The increased abundance and prolonged host-seeking activity of *Cx. tarsalis* during the spring and early summer following a strong El Niño may have a significant impact on public health in urban southern California because this mosquito is an important arbovirus vector and constructed wetlands in urban areas may increase suitable, comparatively permanent developmental sites for important mosquito vectors such as *Cx. tarsalis* that are usually rare in urban environments. *Journal of Vector Ecology* 33 (1): 17-29. 2008.

Keyword Index: ENSO, El Niño, mosquito ecology, *Culex*, wetlands.

INTRODUCTION

Long-term changes (Reeves et al. 1994, McMichael and Martins 1995, Jetten and Focks 1997, Martens et al. 1997, Patz et al. 1998, Epstein 2000, Hopp and Foley 2001) and interannual variation (Nicholls 1993, Lindblade et al. 1999, Reisen 2002) in climate are thought to influence the factors affecting vector populations and pathogen transmission. El Niño and La Niña are alternate states of the El Niño - Southern Oscillation (ENSO) and refer to disruptions of the ocean-atmosphere system of the equatorial western Pacific Ocean (approximately between 5°N and 5°S, and 120° and 170°W) that affect air temperature and the distribution of precipitation on a broad geographical scale with a periodicity of about two to seven years.

ENSO events alter the air temperature and rainfall patterns of the Mediterranean climate of southern California which is characterized by hot, dry summers and cool winters with rainfall concentrated during the late autumn and winter. The displacement of the jet stream during El Niño conditions characteristically causes more rainy days, with more rainfall per precipitation event, than is typical in southern California (Climate Prediction Center 2005a). Mean rainfall during El Niño periods is 127% normal (mean for the 102-year period 1895-1996) during November and December and 140% normal during January through March

for southern California (Climate Prediction Center 2005a). Even though the annual mean temperature in southern California during El Niño events does not differ significantly from the long-term average, air temperatures during the predominant period of precipitation in southern California's Mediterranean climate can be slightly cooler than normal (Climate Prediction Center 2005b). However during strong El Niño conditions, late winter and spring temperatures calculated as three-month means (March-May, April-June) are typically warmer than normal in southern California (Western Regional Climate Center 1998, Climate Prediction Center 2005b). Less rainfall and cooler temperatures than the long-term averages characterize early-year conditions of La Niña in southern California.

The changes in precipitation and air temperature associated with ENSO events are expected to affect mosquito populations. Changes in precipitation patterns alter the quality and quantity of mosquito larval habitats, resulting in changes in mosquito abundance (Wegbreit and Reisen 2000, Shaman et al. 2002, Bolling et al. 2005) and pathogen transmission rates (Shaman and Day 2005). Rates of egg development and immature mosquito development are directly related to temperature (Bailey and Geike 1968, Miura and Takahashi 1988). Changes in the weather associated with ENSO events may also affect the species composition of mosquitoes by altering seasonal patterns of

abundance and host-seeking activity.

The impact of concomitant changes of precipitation and temperature before and during a comparatively strong ENSO event (the 1997-1998 El Niño and the 1998-1999 La Niña: Western Regional Climate Center 1998, Climate Prediction Center 2005a) on host-seeking and gravid mosquito abundance and species composition in the region surrounding a degraded saltmarsh in western Los Angeles County, CA, was the focus of this study.

MATERIALS AND METHODS

Host-seeking and gravid mosquito populations were sampled within a degraded saltmarsh (Ballona Wetlands) and in the region surrounding (≤ 2.25 km) the wetlands that is included in the Playa Vista Development Project in western Los Angeles County, CA. The wetlands restoration and urban development components of the Playa Vista Development Project were situated adjacent to residential and urban zones of Culver City, CA. Restoration of approximately 76 ha of degraded saltmarsh adjacent to Ballona Creek and 14 ha of uplands habitat including a dune area near bluffs on the southern edge of the saltmarsh, and construction of a 14-ha freshwater wetland with associated riparian habitat were to be undertaken as mitigation measures for the housing and commercial development. Twelve sites (between 33°57'47" N and 33°58'54" N, between 118°24'7" W and 118°27'36" W) were chosen to be representative of four habitats in the restoration project: prospective freshwater wetlands/riparian zones, degraded saltmarsh, abandoned land that was previously developed (land formerly associated with the Hughes Aircraft plant), and bluffs below existing houses and development. Saltmarsh restoration and freshwater marsh/riparian area construction were carried out after this study was completed; the sampling sites used in this study were unlikely to have been affected by other development activities. Heft (2001)³ provides a detailed description and land-use history of the trapping sites.

Climatic data were obtained from the California Irrigation Management Information System (CIMIS: State of California Department of Water Resources) Santa Monica station (34°02'28" N, 118°28'34" W; 104 m ASL) located 8 km northwest of the Ballona Wetlands. Daily minimum air temperature, maximum air temperature, average daily air temperature (calculated as the daily mean for hourly mean temperatures), and daily precipitation were used over the study period, December 1996 through November 1999. Because the Santa Monica CIMIS station began operation in December 1992, climatic data from the station might provide less reliable long-term means for weather variables than would means based on a more extensive data set. Bi-weekly values of normal precipitation (sum for 2-week periods) and mean daily temperature were calculated using daily precipitation and temperature at Santa Monica Pier,

CA, (station no. 047953; 34°00' N, 118°30' W; 77.4 m ASL), for a twenty-nine-year period (1971-2000) obtained from the NOAA Western Regional Climate Center (<http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?casmon>).

Adult mosquitoes were sampled weekly from April through October and bi-weekly from November through March beginning in December 1996 until December 1999. A Centers for Disease Control (CDC)-CO₂ trap and a Reiter-Cummings (Cummings 1992) gravid mosquito trap (Bioquip Products, Gardena, CA) were placed at each of the 12 trapping sites. Each CDC-CO₂ trap was baited with approximately 2.2 kg dry ice. Each gravid mosquito trap was baited with 9.5 liters of alfalfa infusion. The infusion (170 liters water, 3.8 liters of alfalfa, 237 ml albumin, 30 ml Brewer's yeast) was aged outdoors for one to two weeks before use. Mosquitoes collected after approximately 24 h were returned to the laboratory and identified to species under 30X magnification using Meyer and Durso (1999).

Bi-weekly means of host-seeking or gravid mosquito abundance were calculated for each species across trap sites. CDC-CO₂ trapping data were $(x + 1)^{1/2}$ transformed. Gravid trap counts were $\log(x + 1)$ transformed. Transformations were determined using Taylor's Power Law (Elliott 1977).

The abundance of each mosquito species and the abundance of all species combined were compared among quarters of the year (January-March, April-June, July-September, October-December) using Kruskal-Wallis tests. Quarters of the year were also classified into one of three categories: El Niño, La Niña, and normal. These categories were based upon reanalyzed sea surface temperature analyses produced at the National Centers for Environmental Prediction/Climate Prediction Center and at the United Kingdom Meteorological Office (Climate Prediction Center 2005b). A MANOVA (SAS 1993, v. 6.12) was used to determine if there was a statistically significant difference among trap results collected during the three weather categories.

Canonical correspondence analysis (CCA) (CANOCO for Windows, ver. 4.54; ter Braak and Smilauer 1998) was used to examine the relationship between mosquito species with environmental variables. Environmental variables were either summed (log-transformed precipitation) or averaged (temperature) bi-weekly. Environmental variables included long-term mean precipitation, long-term mean daily temperature, precipitation, daily mean temperature, precipitation at two or four weeks prior to the mosquito sample, mean temperature at two or four weeks prior to the mosquito sample, and a standardized measure of temperature variation (i.e., the deviation from the long-term mean daily temperature). Interaction terms for the precipitation and temperature variables were also included in the multiple regressions used to constrain the sample (= site) scores during ordination. An ordination biplot was used to illustrate the relationship between species composition

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of the five dominant host-seeking mosquito species in trap catches and the environmental conditions in 76 bi-weekly samples during the three years of the study. A multiple regression model with a maximum of six environmental variables was assessed for the entire study. The statistical significance of each environmental variable in the final model was determined using Monte Carlo permutation tests (permutations = 499).

Archived trapping data

Trends of mosquito abundance in CO₂-baited suction trap and gravid trap collections at the Ballona Wetlands trapping site from 1992 through 1996 were examined using archived data at the Los Angeles County West Vector Control District (Culver City, CA). Collection data for each trap type had been combined and stored as a single value for each trapping date. Dates on which at least one gravid trap was deployed were considered and standardized to a single gravid trap when more than one gravid trap had been deployed. A single trap of each type was deployed on 76% of the dates across the four years. Gravid traps were deployed too infrequently to provide a comparable measure of mosquito abundance during 1996.

RESULTS

Environmental conditions

The mean daily temperature during 1997 exceeded the long-term average on more days (67%) than during 1998 (42%) and 1999 (28%) and was 514 degree-days higher than the long-term average as compared to -26.3 degree-days during 1998 and -191.3 degree-days during 1999 (through November 30). During the first half of 1997, mean daily temperature was up to 7° C higher than the long-term mean daily temperatures and comparatively elevated temperature was evident from 25 April (day 115) through 19 July (day 200; Figure 1A). An extended period [from approximately 8 August (day 220) through early October (day 280)] of warmer than average temperatures also occurred during the second half of 1997, and late October and November were appreciably warmer than usual (Figure 1A). Mean monthly precipitation from February through April was about 3% of the long-term mean for the same period (Figure 2). Towards the end of 1997, mean monthly rainfall was above the long-term mean for the region as El Niño conditions began.

Rainfall increased during the first part of 1998, reaching a peak in February (951 mm) at 11.4-times above long-term mean precipitation for the month (Figure 2). Mean daily temperature was below the long-term average for most of the first half of 1998 indicating a cool spring and early summer (Figure 1B). Daily mean temperatures during 1998 were above the long-term average from 19 July (day 200) through 7 September (day 250) and below the long-term average during much of autumn.

Mean daily temperature was below the long-term average during most of 1999 between February and early October, except for a brief period during late April and late summer (Figure 1C). Rainfall during 1999 was considerably

below average for much of the year, 71% of normal precipitation levels through November, creating cool and dry La Niña conditions (Figure 2). Very little precipitation typically occurs from April until November in southern California; however, April (37 mm vs. 13 mm) and June (18 mm vs. 1 mm) were uncharacteristically wet because a single storm event occurred in each month.

Mosquitoes

The total number of mosquitoes collected in CO₂-baited suction and gravid traps was 6,030 and 23,108, respectively. Host-seeking mosquitoes included eleven species in three genera (Table 1). *Culex quinquefasciatus* was the most prevalent species collected by gravid traps. *Culex restuans* Theobald and three *Ochlerotatus* species were never collected by gravid traps.

The seasonal pattern of abundance of the five dominant mosquito species collected by CO₂-baited suction traps differed among the three years of the study (Figure 3) and differed significantly among the quarters of each year during the study (Kruskal-Wallis tests: $\chi^2_{12} > 54.0$, $P < 0.0005$). Adult host-seeking mosquito populations collected during El Niño and La Niña conditions differed significantly in both abundance and composition from those collected during 1997 (MANOVA: $F_{2,20} = 22.820$, $P = 0.043$).

Culex quinquefasciatus was present year-round and the seasonal population distribution varied among years more than the other species (Figure 3A). Host-seeking population abundance was highest during 1997 and was trimodal with peaks in January, June, and late September; with the greatest number of individuals collected during the summer and autumn. *Culex quinquefasciatus* host-seeking populations during 1998 and 1999 were smaller than during 1997, and were bimodal in 1998 with peaks in June and late September-early October and unimodal in 1999 with an abundance maximum in August.

Culex erythrothorax was rarely collected during summer 1997 and 1998 and increased in abundance during 1999 (Figure 3A). This species was nearly 9% of host-seeking individuals collected during the La Niña period (Table 1).

Culex tarsalis exhibited a bimodal seasonal abundance pattern with annual vernal and autumnal peaks (Figure 3A). This species constituted between 7.5 and 19% of host-seeking individuals collected during the three weather periods. The abundance of host-seeking individuals peaked early in the warmest year (February 1997) and was depressed during both the remainder of 1997 and during the cold, dry spring of 1999. Host-seeking populations were enhanced by three- to six-fold relative to other years following the wet period of the 1998 El Niño.

Cool-weather mosquitoes, *Culiseta inornata* (Williston) and *Cs. incidens* (Thomson), dominated host-seeking mosquito collections during late autumn and winter (Figure 3B). The annual peaks of *Cs. inornata* host-seeking individuals preceded those of *Cs. incidens* and the temporal occurrence of *Cs. inornata* host-seekers during the El Niño (seven months) was broader than during 1997 and 1999 (three to three and one-half months). Following the El Niño

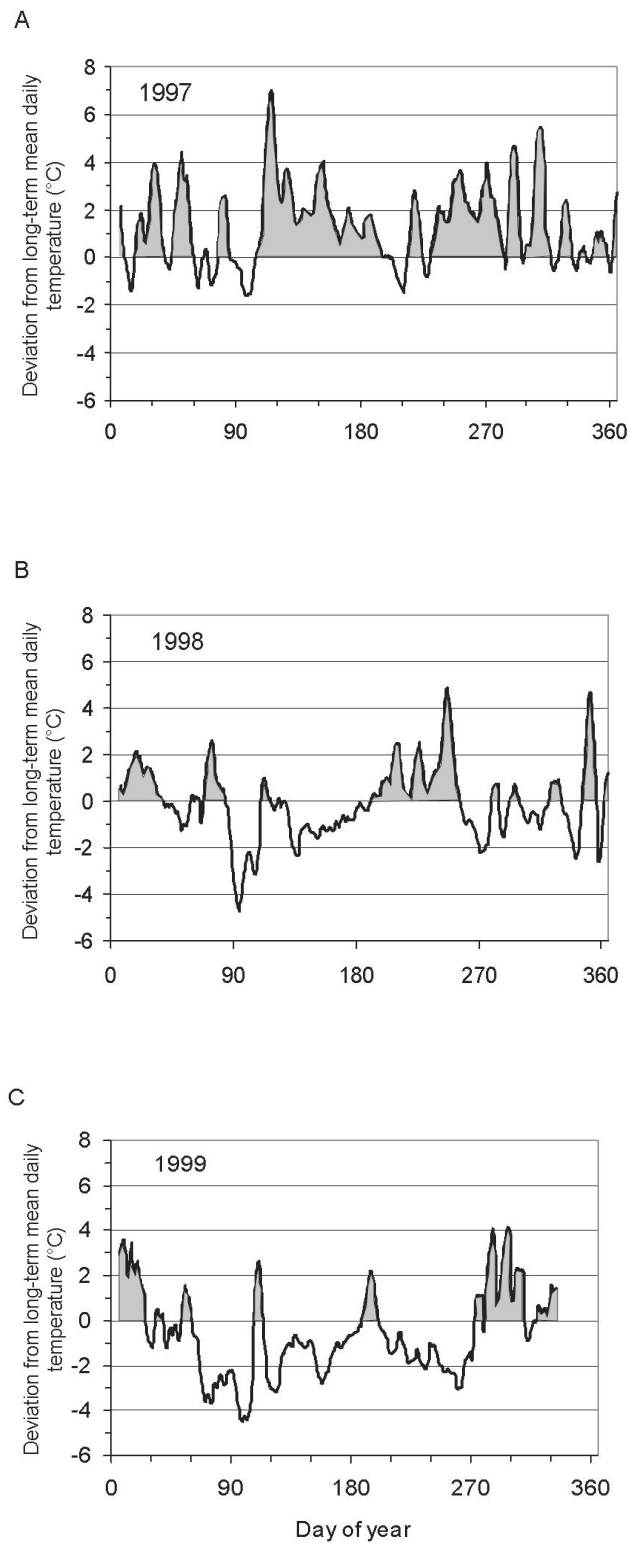


Figure 1. Deviation from the long-term daily mean temperature (1971-2000) recorded at Santa Monica, California during (A) 1997, (B) 1998, and (C) 1999. The seven-day moving mean is illustrated for each year. Periods of daily mean temperatures above the long-term daily mean temperature are highlighted by gray shading.

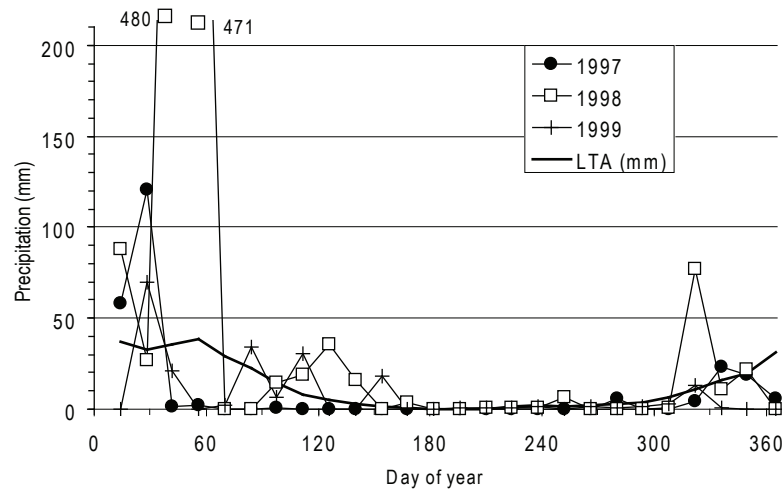


Figure 2. Bi-weekly total precipitation recorded in Santa Monica, CA, during the period of 1997-1999. The long-term average (LTA) bi-weekly precipitation recorded over period 1971 to 2000 is illustrated.

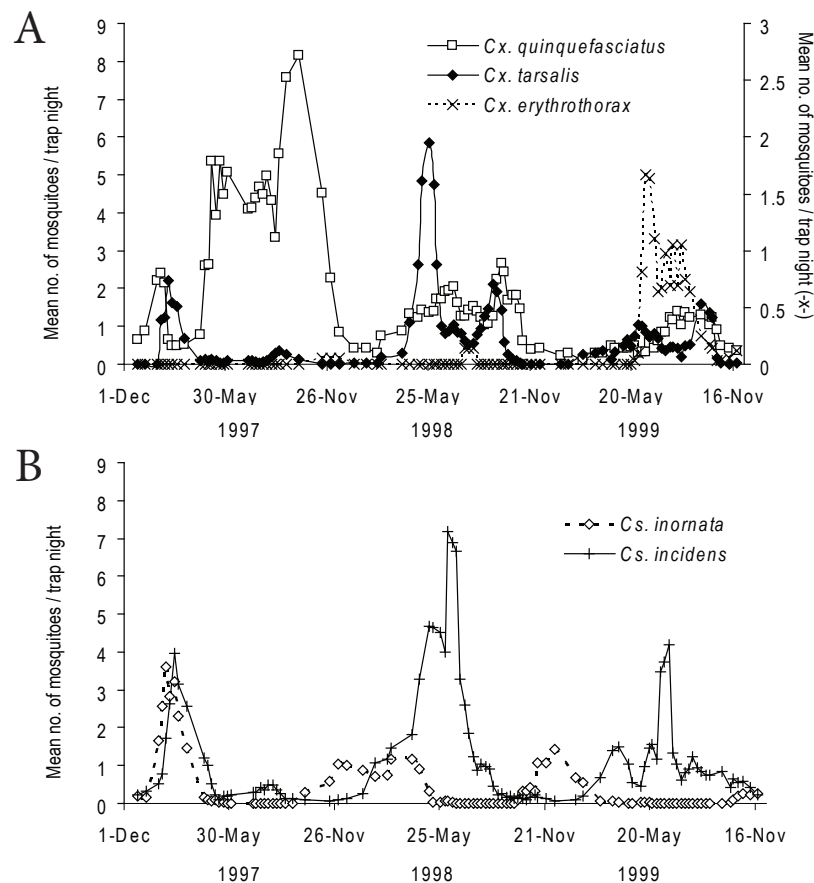


Figure 3. The seasonal abundance of the dominant host-seeking mosquitoes (A: *Culex*; B: *Culiseta*) caught per trap night during 1997-1999. A three-point moving average of backtransformed mean abundance for each species is illustrated.

Table 1. Relative abundance (%) of mosquito species collected in two trap types in western Los Angeles County during 1997 through 1999.

Species	January – September 1997		El Niño: October 1997- June 1998		La Niña: July 1998 – December 1999	
	CO ₂ - baited suction	Gravid	CO ₂ - baited suction	Gravid	CO ₂ - baited suction	Gravid
<i>Culex tarsalis</i> Coq.	7.47	0.77	17.61	2.68	19.20	3.47
<i>Culex quinquefasciatus</i> Say	60.60	93.14	27.23	94.59	33.31	93.66
<i>Culex stigmatosoma</i> Dyar	0.34	1.52	0.13	0.24	0.32	0.47
<i>Culex erythrothorax</i> Dyar	0	0.02	0.26	0	8.83	0.07
<i>Culex restuans</i> Theobald	0	-	0	-	0.06	-
<i>Culiseta inornata</i> (Williston)	13.00	0.15	13.81	1.05	6.31	0.15
<i>Culiseta incidens</i> (Thomson)	15.62	4.39	40.77	1.44	31.83	2.18
<i>Ochlerotatus squamiger</i> (Coq.)	2.85	0.02	0	0	0.06	0
<i>Ochlerotatus taeniorhynchus</i> (Wiedemann)	0.11	-	0	-	0.06	-
<i>Ochlerotatus nigromaculis</i> (Ludlow)	0	-	0.06	-	0	-
<i>Ochlerotatus washinoi</i> Lanzaro & Eldridge	0	-	0.13	-	0	-

- indicates that this species was never collected in gravid traps.

rains, *Cs. incidens* was the dominant host-seeking mosquito (41% of individuals) during the second quarter of 1998 but, unlike 1997, host-seeking activity of this species extended into the early summer. During the cool, dry La Niña year of 1999, the abundance of host-seeking *Cs. incidens* was lower than during 1998 but individuals were again collected throughout the summer and autumn (Figure 3B).

Gravid mosquito abundance was enhanced by precipitation following El Niño conditions and reduced under the cool, dry conditions of La Niña. *Culex quinquefasciatus* was the dominant species collected in gravid traps (> 90% of individuals collected; Table 1); the species composition of gravid mosquitoes did not differ significantly (MANOVA: $F_{6,14} = 1.529$, $P = 0.313$) during the study. Gravid mosquito abundance during the fourth quarter (4Q) 1997 (~40 mosquitoes/trap night) differed substantially from gravid mosquito abundance observed during 4Q 1998 (La Niña: ~15 mosquitoes/trap night) and 4Q 1999 (La Niña: ~seven mosquitoes/trap night) (Figure 4). Gravid mosquito collections during the spring 1999 also were low. Gravid trap catches of *Cx. quinquefasciatus* increased during the summer and autumn 1997, peaking during autumn-early winter 1997-1998 as the rains of the El Niño began.

The relationship of the host-seeking mosquito species composition to the environmental variables is illustrated in the CCA-triplot (Figure 5). Temperatures 2 weeks prior to samples had the greatest influence on the host-seeking mosquito community across the three years of the study (Table 2). Temperatures 4 weeks prior to samples, deviation from the long-term average temperature, and the interaction between temperature deviation and precipitation four weeks prior to samples had lesser, but significant, conditional effects on the host-seeking mosquitoes (Table 2). The inverse relationship between the period of annual maximum precipitation and annual maximum temperature is illustrated by the opposite directions of the vectors for these environmental variables in the ordination plot (Figure 5), and their significant effects on the host-seeking mosquito community (Table 2) are indicative of the repeatable annual population cycles of the dominant host-seeking mosquito species. The first two ordination axes explained 55% of the variance in the species data during the three-year period.

The position of each mosquito species in the ordination plot is indicative of its preferences for the environmental conditions related to the climatic variables jointly under consideration. *Culex quinquefasciatus* is associated with samples collected during warmer than average periods (i.e., 2Q-97, 4Q-97), which are positioned on the left of the ordination, and with the third quarters of each year (Figure 5). *Culiseta inornata* is associated with cold, wet periods such as the first and fourth quarters of each year which are positioned in the upper half of the ordination. The effects of cool temperatures on immature development times presumably account for the association of this mosquito with the interaction between deviation from normal temperatures and rainfall four weeks before the samples. Peak production of *Cx. tarsalis* and *Cs. incidens* occurs

Table 2. Conditional effects of environmental factors influencing the abundance of the five dominant host-seeking mosquito species during a three-year period (1997 to 1999) at the Playa Vista Development Project, Los Angeles County, CA.

Variable	λ -A ¹	F ²	P
2-week lag temperature	0.28	31.56	0.002
LTA ³ temperature	0.15	22.96	0.002
4-week lag temperature	0.04	6.43	0.002
LTA precipitation	0.02	3.59	0.01
Deviation from LTA temperature	0.02	2.96	0.02
Deviation from LTA temp* 4-week lag in precipitation	0.02	2.77	0.05

¹Additional variance explained by adding the variable to the multiple regression model.

²F-test for Monte Carlo permutation test.

³LTA = long-term average.

during June of most years and both species were associated with cooler than normal periods such as 2Q-98, 2Q-99, and 3Q-99. *Culex erythrothorax* is associated with warm times of the year, especially during 1999.

Mosquito trends during 1992-1995

As compared to 1997-1999, environmental conditions during 1992-1995 deviated little from normal conditions. Among the four years 1992-1995, a comparatively weak El Niño occurred during the winter 1991-1992. Three-month running mean temperatures (SST anomalies in the western Pacific Ocean) were $\geq 1^\circ \text{C}$ above the long-term mean beginning in September-October-November 1991 through April-May-June 1992. Weak warming trends (three-month running mean temperature deviations for SST anomalies $\leq 0.8^\circ \text{C}$ above the long-term mean) were observed in late winter 1993 and again during late 1994 through early 1995. A weak La Niña occurred in winter 1995-1996.

Among the four years, annual rainfall was greatest during 1995 (mean precipitation for CIMIS and WRCC stations: 650 mm) and was least during 1994 (mean: 239 mm) when conditions were more similar to the 1999 La Niña (Figure 6A). Rainfall during 1992 (WRCC station: 442 mm) and 1993 (mean: 637 mm) exceeded the long-term mean for Santa Monica (337 mm). Late 1992 and early 1993 was a comparatively wet period but the rainfall totals

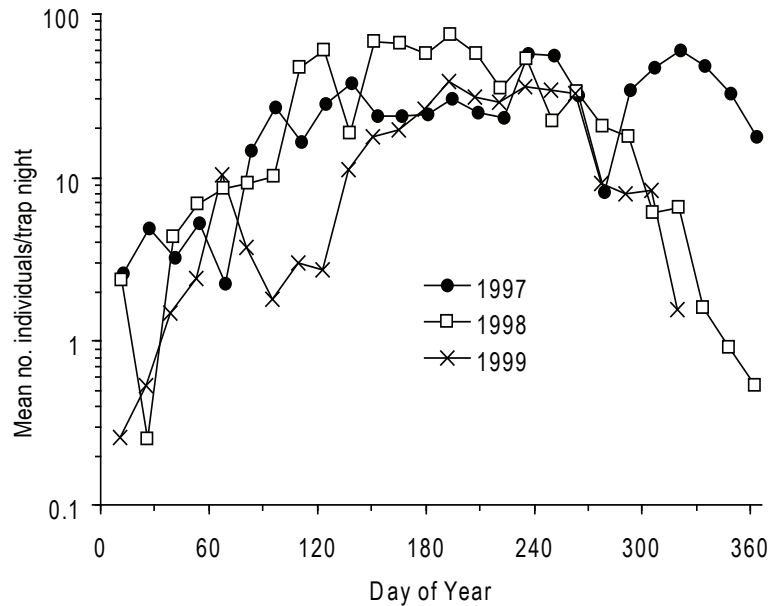


Figure 4. The mean abundance of gravid mosquitoes caught per trap night by 12 Reiter-Cummings gravid traps at the Ballona Wetlands and surrounding region, Los Angeles County, CA, during 1997-1999.

for 1993 were not comparable at the two weather stations (WRCC: 469 mm vs CIMIS: 805 mm). After January 1993, dry conditions prevailed for the remainder of the year.

The trapping data for 1992-1995 were strongly influenced by gravid *Cx. quinquefasciatus* because more mosquitoes were collected by gravid traps than by CO₂-baited suction traps and *Cx. quinquefasciatus* was prevalent in gravid trap collections. Collections of gravid *Cx. quinquefasciatus* were reduced noticeably during the spring through the end of July 1992 following the El Niño rains (Figure 6B). Mosquito collections from August until November 1992 were at levels comparable to other years, except 1995 when trap collections were lower during late autumn. The number of mosquitoes in collections from late April (day 120) through early July (~ day 190) 1993 was > 1994 > 1995. Beginning in late summer, trap catches were variable across years, but fluctuated around 60 individuals per trap night during late summer and autumn.

Two ENSO-related trends of mosquito abundance observed during 1997-1999 were observed during 1992-1995. *Culex quinquefasciatus* populations were reduced by rains associated with El Niño and mosquito collections were comparatively low at the beginning of the weak La Niña in 1995. *Culex tarsalis* collections were high from February through April 1993, but were too infrequent during other periods to make conclusive statements about abundance trends. *Culiseta* spp. also did not respond strongly to the comparatively small changes in mean temperature observed during 1992-1995.

DISCUSSION

ENSO cycles during 1997-1999 significantly altered the abundance and species composition of the mosquito community at the Playa Vista Development Project in western Los Angeles County, CA. The substantial increase in rainfall during the winter 1997-1998 significantly increased mosquito abundance within the degraded Ballona Wetlands and in the surrounding region. Temperature conditions during the El Niño favored cool-weather mosquito species. Host-seeking mosquito species composition changed from a typical pattern of dominance by cool weather species in early spring followed by dominance of *Cx. quinquefasciatus* beginning in the late spring to dominance by species associated with cooler temperatures, such as *Cx. tarsalis* and *Cs. incidens*, throughout spring and into the summer during strong El Niño conditions. *Culex tarsalis* and *Cs. incidens* remained prevalent into the summer during the relatively cool conditions of La Niña, although at much lower abundance than after the El Niño. The comparatively dry conditions of La Niña caused a decline in mosquito abundance amongst all mosquito species.

The heavy rainfall during the winter of 1998 had a negative effect on *Cx. quinquefasciatus* host-seeking populations during the first quarter of the year through early summer. Shaman and Day (2005) suggested that rainfall influences mosquito life cycles in two ways: increasing near-surface humidity that enhances flight activity and host-seeking behavior and, secondly, altering the availability of mosquito developmental sites. Rainfall in the Mediterranean climate of southern California occurs predominantly during months (November through March) of normally low mosquito activity. Suburban/

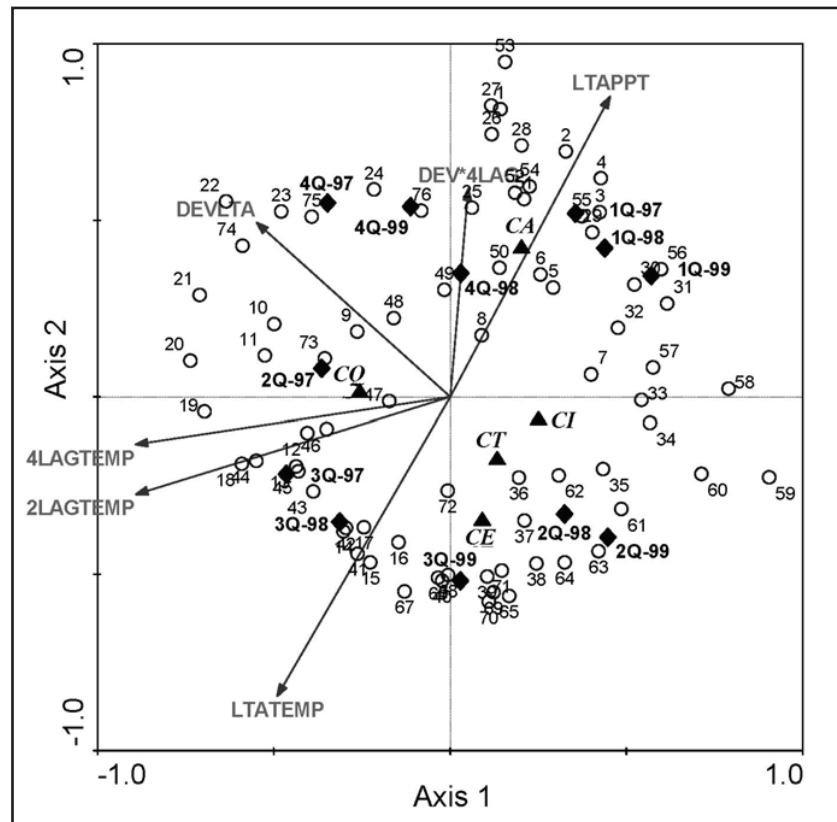


Figure 5. Ordination triplot of the dominant host-seeking mosquito species in bi-weekly samples (○: 1997:1-26; 1998: 27-52; 1999: 53-76) on environmental variables for canonical variates 1 and 2 of a canonical correspondence analysis (CCA). (mosquito species (▲): CA = *Culiseta inornata*, CE = *Culex erythrothorax*, CI = *Culiseta incidens*, CQ = *Culex quinquefasciatus*, CT = *Culex tarsalis*; environmental variables: LTAPPT = long-term average for (log-transformed) precipitation across two-week periods, LTATEMP = long-term average for mean daily temperatures across two-week periods, 4LAGTEMP = bi-weekly average temperature at four weeks before the mosquito sample; 2LAGTEMP = biweekly average temperature at two weeks before the mosquito sample, DEVLTA = deviation from the long-term mean daily temperature averaged bi-weekly, DEV4LAG = the interaction between deviation from the long-term mean daily temperature averaged bi-weekly and (log-transformed) precipitation during a 14-day period four weeks before the mosquito sample. Long-term averages are based on the period 1971-2000 at Santa Monica, CA. The centroids for the four quarters (Q) of each year (◆) are labelled with a quarter number and a two-digit year code.

urban irrigation runoff and sporadic rainfall associated with convective processes, mostly in upslope areas along the mountains, provide water for mosquito developmental sites during the dry period of the year. Much of the urban breeding habitat of *Cx. quinquefasciatus* around the Ballona Wetlands is catchment basins and sumps (e.g., storm drains, catch basins, underground drains, sewer lines) that hold water because of poor design, improper grading, or clogging by debris and sand (Heft, personal observation; Reisen 2002). Heavy rainfall scoured and unclogged storm drains and sewer lines, removing sources of standing water that provided potential sites of *Cx. quinquefasciatus* production. Shaman et al. (2002) found that the abundance of the closely related congener, *Cx. pipiens*, in rural New Jersey was negatively related to modeled surface wetness. They postulated that flushing of larval developmental sites and a direct relationship between levels of eutrophication and shrinkage of surface waters caused a negative

association of the northern house mosquito adults and surface wetness. Although the abundance of host-seeking *Cx. quinquefasciatus* was reduced during the second quarter of 1998, gravid individuals increased to the highest abundance recorded during the three years of the study. The loss of potential breeding sites in standing water in storm drains and sewer lines near the Ballona Wetlands might have increased the attractiveness of the gravid trap to *Cx. quinquefasciatus* females seeking sites for egg laying.

The temporal trends for gravid mosquito abundance differed among the three years of the study; however, gravid mosquito species composition was not significantly affected by ENSO cycles. Relative to spring 1997, gravid mosquito abundance increased two- to three-fold during the late spring and early summer following El Niño conditions. In contrast to 1997 and 1998, gravid mosquito activity was extremely low during La Niña conditions of spring 1999. Even though gravid trap collections indicated that ENSO

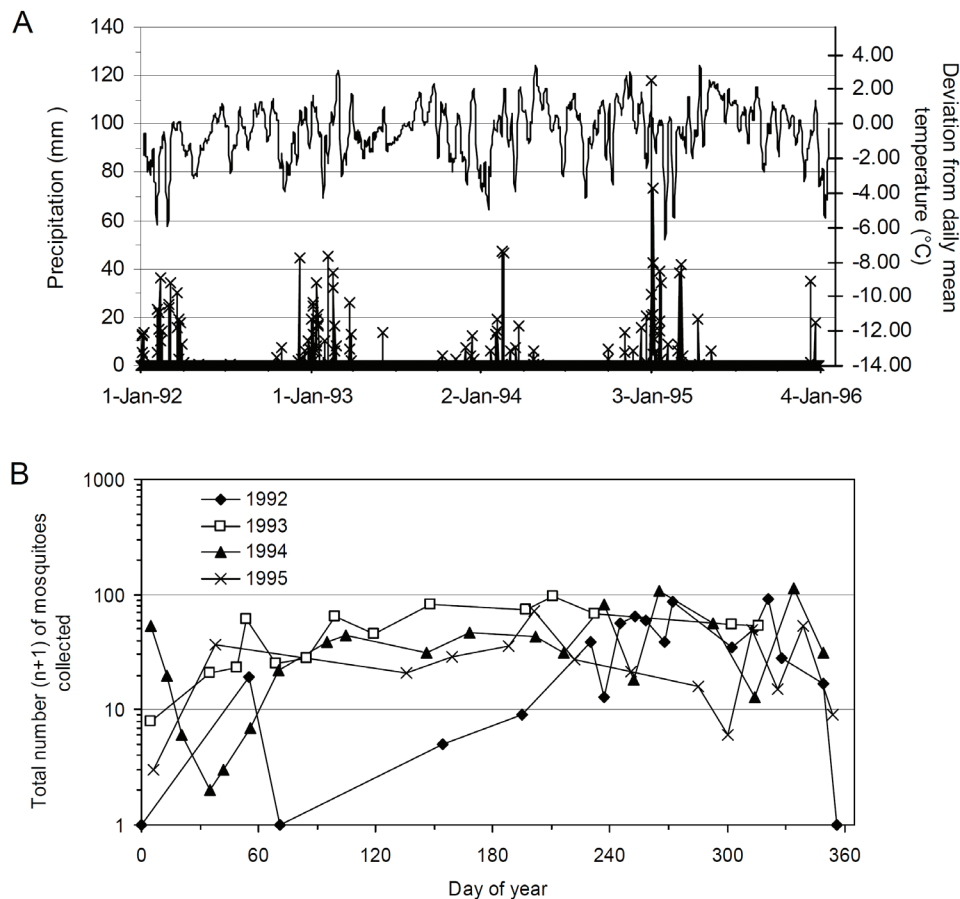


Figure 6. (A) Three-day running average for daily median temperature (1992) or mean temperature (1993-1995) and daily precipitation at Santa Monica, CA and (B) combined collections of mosquitoes from carbon dioxide-baited suction traps and gravid traps at the Ballona Wetlands, Los Angeles County, CA from 1992 through 1995.

conditions affected the numbers of egg-laying mosquitoes, the bias of gravid traps baited with hay infusions for collecting *Cx. quinquefasciatus* in urban-suburban habitats (Reiter 1983, Reisen and Pfuntner 1987, Reisen and Meyer 1990) limits the ability of this trapping method to detect changes in mosquito species composition. Broadening of the gravid species catch might reveal a closer relationship between gravid and host-seeking mosquito population fluctuations than was present in this study. Alternate bait infusions, such as bulrush infusion (Walton and Workman 1998), could be used to broaden the range of species collected in future studies.

The tule mosquito, *Cx. erythrothorax*, is associated with developmental sites containing comparatively dense stands of emergent vegetation (Meyer and Durso 1999) that are rare in regions of urban development and are probably influenced by ENSO-related changes in weather to a lesser degree than are the developmental sites of *Cx. tarsalis* and *Cx. quinquefasciatus*. Even though *Cx. erythrothorax* can transmit WNV (Goddard et al. 2002), infrequent arbovirus infections (CDHS 2006b) and host preferences (Walton et al. 1999) suggest that this species does not have a major role in transmission of WNV. Host-seeking by *Cx. erythrothorax*

extends from spring until late autumn (Cope et al. 1986, Walton et al. 1998) and can occur during winter if conditions warm sufficiently in southern California (Walton, personal observation). Collections of host-seeking *Cx. erythrothorax* increased in traps near Centinela Creek in summer 1999 and may be indicative of the re-establishment of emergent vegetation on the periphery of the creek channel.

On an annual basis, the abundance of host-seeking mosquitoes at the Ballona Wetlands during 1998 was two-fold greater than that observed during 1999 and the mosquito fauna (collected by carbon dioxide-baited suction traps) was strongly influenced by the wetlands proximity to urban environments. Heft (2001)³ observed comparable annual changes of host-seeking mosquito abundance at wetlands 59 km northwest (Point Mugu: two-fold difference) and 48 km southeast (Bolsa Chica Wetlands: 2.6-fold difference) of the Ballona Wetlands. The mosquito fauna at trapping sites adjacent to the Bolsa Chica Wetlands was similar to the mosquito fauna collected at the Ballona Wetlands, was also strongly influenced by mosquito (*Cx. quinquefasciatus*) production from the surrounding urban area, and the monthly (ln-transformed) abundance of host-seeking mosquitoes in carbon dioxide-baited suction trap

collections was significantly associated ($r = 0.71$; $P < 0.01$) at the wetlands. The Pt. Magu wetlands are surrounded by comparatively rural habitat and the mosquito fauna was dominated by *Cx. tarsalis* and the multivoltine *Oc. taeniorhynchus* (Wiedemann). Although the ratio of interannual differences of mosquito abundance in trap collections was comparable at the Pt. Mugu and Ballona wetlands and trap collections (ln-transformed) at the two wetlands were strongly correlated ($r = 0.64$; $P < 0.01$), the abundance of host-seeking individuals at Pt. Mugu during annual peak production (July – September) was typically an order of magnitude higher than at the Ballona Wetlands (Heft, 2001³). Examination of the population trends for mosquitoes across a longer period than three years might provide a more robust assessment of the effects of short-term oscillations in climate associated with ENSO events; however, the comparable responses of mosquito populations both at other wetlands and historically at the Ballona Wetlands indicate that the effects of ENSO are not unique to the Ballona Wetlands during the three years of this study.

The heightened abundance of the host-seeking *Cx. tarsalis* and gravid *Cx. quinquefasciatus* populations observed after El Niño events could have a potential public health impact, especially with the addition of treatment wetlands to an urban landscape. *Culex tarsalis* is the primary vector of SLE (Reeves and Hammon 1962, Emmons et al. 1988) and an efficient vector of WNV (Goddard et al. 2002), primarily outside urban regions. Studies in Kern County, CA, showed that wet winters and concurrent heavy river flow that inundated floodplains in the spring and early summer usually produced rapid increases in *Cx. tarsalis* abundance (Reeves and Hammon 1962). *Culex quinquefasciatus* is considered the primary vector of WNV in urban environments (Nasci et al. 2001, Wilson et al. 2004). Ovipositional activity of this species was enhanced during the winter as El Niño conditions began and after the period of rainfall. An increase in abundance of either of these mosquitoes could lead to heightened arbovirus transmission to humans, especially in western Los Angeles County where a freshwater constructed treatment wetland supporting reservoirs for the arboviruses will be surrounded closely by human development in the city of Los Angeles. The relative importance of *Cx. quinquefasciatus* vs *Cx. tarsalis* in arbovirus transmission cycles where treatment wetlands abut urban land uses merits further study.

Constructed treatment wetlands situated in urban environments have the potential to alter the seasonal abundance and species composition of mosquitoes, especially in arid climates (Walton 2002). Arbovirus activity has been recorded historically at the Ballona Wetlands as SLE antibody presence in the wild bird population and as seroconversions to SLE in sentinel chickens (Los Angeles County West Vector Control District, unpublished data), as well as the more recent (2004) detection of WNV exposure in sentinel chickens (CDHS 2006a). Arbovirus activity was not detected in the mosquito populations during the current study (Heft 2001³); however, the low numbers of host-seeking mosquitoes characteristic of the urban

environs did not exceed the minimum threshold (≥ 50 individuals per species) required for submission of mosquito pools for arbovirus testing on most sampling dates. The freshwater wetland used to treat urban runoff entering the restored Ballona Wetlands saltmarsh has the potential to provide habitat for mosquitoes, such as *Cx. tarsalis* and *Cx. erythrothorax*, that do not occur commonly in urban environments. The abundance of host-seeking mosquito populations of these two species near constructed wetlands is a function of several factors, especially water quality and the coverage of the water surface by emergent macrophytes, and host-seeking mosquito collections are often several orders of magnitude (several hundred to several thousand female mosquitoes per trap night: Walton et al. 1998, Keiper et al. 2003) higher than those recorded in this study. Whereas studies of the effects of other ENSO events on mosquito populations in southern California are needed to confirm the generality of our findings, changes in mosquito communities caused by ENSO events could be exacerbated if renovated or created wetlands at the suburban-urban interface produce mosquitoes of public health significance.

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