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Outdoor residential water use restrictions during recent drought suppressed disease vector abundance in Southern California

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Abstract

The California state government put restrictions on outdoor residential water use, including landscape irrigation during the 2012–2016 drought. The public health implications of these actions are largely unknown, particularly with respect to mosquito-borne disease transmission. While residential irrigation facilitates persistence of mosquitoes by increasing the availability of standing water, few studies have investigated its effects on vector abundance. In two study sub-regions in the Los Angeles Basin, we examined the effect of outdoor residential water use restrictions on the abundance of the most important regional West Nile virus vector, *Culex quinquefasciatus*. Using spatiotemporal random forest models fit to *Cx.* abundance during drought and non-drought years, we generated counterfactual estimates of *Cx.* abundance under a hypothetical drought scenario without water use restrictions. We estimate that *Cx.* abundance would have been 44% and 39% larger in West Los Angeles and Orange counties, respectively, if outdoor water usage had remained unchanged. Our results suggest that drought, without mandatory water use restrictions, may counterintuitively *increase* the availability of larval habitats for vectors in naturally dry, highly irrigated settings and such mandatory water use restrictions may constrain *Cx.* abundance, which could reduce the risk of mosquito-borne disease while helping urban utilities maintain adequate water supplies.

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Author contributions

A.B. and N.K.S. designed the study, analyzed the data, prepared the figures and wrote the manuscript. All authors discussed the results and commented on the manuscript.

Supporting Information

Random forest model performance (between model predicted *Cx.* abundance and surveillance observations) for two study sub-regions for the training period (2006–2013) and counterfactual evaluation period (2014–2016), spatially aggregated average weekly (ln) observed and predicted abundance of *Cx.* abundance from 2010–2016, time series of residential daily per capita water use and outdoor residential daily per capita water use, and percent reduction in each month relative to water deliveries in 2013 for each urban water supplier in West LA and Orange County sub-regions, and the permutation importance of top 10 environmental predictors for each study sub-region

Introduction

The 2012–2016 California drought was unprecedented because of its severity and accompanying record warm temperatures.[1] Observed precipitation during 2013 was the lowest consecutive 12-month accumulated total in the 119-year observational record. The 3-year anomaly from December 2011 to September 2014 was larger than any previous recorded drought anomaly since 1895 including the 1976–77 drought.[2, 3] The combination of dry and warm conditions during the 2012–2016 drought severely stressed ecosystems and human communities in California.[1–6] Despite the historic nature of the 2012–2016 drought and disproportionate impacts to rural areas within California, domestic water availability in urban regions of California was only mildly affected partly because of the vast water conveyance system the state has developed to deliver water to densely populated urban regions,[4] and partly because of aggressive urban water conservation strategies implemented by the California State Water Resources Control Board (SWRCB). In particular, Governor Jerry Brown issued an executive order on April 1, 2015 that urban water utilities reduce water delivery by 25% relative to 2013 levels.[7] In California, residential water use (both indoor and outdoor) is typically the largest urban water use category (~60%), though urban water use represents only 5% of the state's total water use.[8] Landscape irrigation, particularly of lawns, comprises a substantial part of residential water use, exceeding 50% in some parts of the state,[9–11] and it is this category that accounted for most of the mandated reductions[7]. Other restriction measures that were put forward by the SWRCB in non-residential areas included prohibiting irrigation with potable water of ornamental turf on public street medians and outside of newly constructed homes/buildings. Several other restrictions were enacted on residential water use such as prohibiting potable water to wash sidewalks and driveways and use of hoses without automatic shutoff nozzles to wash cars.[7] Southern California, especially the greater Los Angeles metropolitan area, was one the most water stressed regions in California during the drought.[1] During the initial period of the water use restriction mandate (June 2015 – February 2016), reductions of urban water use were estimated to be 21.2% across the region.[12]

The high intensity of the drought in the Los Angeles Basin combined with marked reductions in water consumption in response to water use restrictions has important implications for mosquito populations in the region. Several mosquito-borne viruses are endemic to California and Los Angeles, although West Nile virus (WNV) has by far the highest incidence in human populations.[13, 14] This flavivirus (family *Flaviviridae*, genus *Flavivirus*) cycles between avian populations and *Culex spp.* mosquitoes that rely on stagnant water pools for larval development, including residual surface water made available after landscape irrigation.[15–17] Human cases of WNV occur as a result of spillover from this enzootic transmission cycle, with the Los Angeles area usually accounting for approximately half of all cases in California.[18] The Los Angeles Basin receives little rainfall during the WNV transmission season (typically lasting from June through November with a peak in August-September), and therefore outdoor irrigation can play an important role supporting vector larval development.[15] Of particular importance for mosquitos are stagnant, nutrient-rich water sources, which furnish vector populations with optimal stable aquatic habitats needed for larval development.[19–23] Temperature also plays a critical role in controlling larval development as well as vector abundance and spatiotemporal dynamics of WNV transmission.[24–26] Within the Los Angeles Basin, there is a narrow optimum range temperature range from 21°C to 27°C for WNV transmission.[27] Other ancillary controls such as socioeconomic factors,[22, 28] economic downturn[29] and vector control activities also determine vector abundance. Temperatures in Southern California are most suitable for WNV transmission during the summer and early fall,[27] but the lack of precipitation during this period usually limits the formation of aquatic habitats, and restricts vector utilization of natural water sources.[13, 30, 31] Therefore, anthropogenic sources of water may play an outsized role in supporting larval development and mosquito-borne disease transmission in the region.

Many aspects of neighborhood design, urban infrastructure, and the behavioral choices of urban and suburban dwellers can contribute to the formation of aquatic habitats.[22, 32] Neglected swimming pools, which were especially common in Southern California during times of economic recession, can contribute to increases in vector populations.[22, 29, 33–35] Additionally, stormwater infrastructure, which can retain water during dry periods, also supports vector development in the region.[31, 36, 37] The contribution of residential landscape irrigation, the most prevalent anthropogenic water source during the summer in Southern California, is largely unknown.[15, 38]

The water use restrictions implemented in the 2012–2016 drought provided a natural experiment through which the impact of residential irrigation on mosquito abundance in the Los Angeles Basin could be better understood. This in turn could lead to better understanding of transmission dynamics of WNV, the most common mosquito-borne pathogen in the region.

In this study, we investigate how drought-related reductions in outdoor residential water use affected the abundance of the WNV vector, *Cx. quinquefasciatus*, in two of Southern California's most populous counties, Los Angeles and Orange. We used urban water records from SWRCB from June 2014 through December 2019 to calculate the extent of water use reductions in the two-county sub-regions during the period of outdoor residential water use restrictions (2014–2016). We calculated residential per capita water use from SWRCB's data of public supply water use. We then examined whether outdoor residential water use restrictions in these regions were associated with reductions in *Cx. quinquefasciatus*, and whether differences in compliance with water use restrictions between the sub-regions contributed to differences in their vector abundance. To accomplish this, we compared observed mosquito abundance with predicted mosquito abundance under a counterfactual modeling scenario in which drought occurred, but no outdoor residential water use restrictions were implemented. We hypothesize that the state-mandated outdoor residential water use restrictions during the drought period reduced *Cx. quinquefasciatus* abundance, and that reductions were more extreme in sub-regions with better compliance with water use restrictions.

Methods

Study region

Our study focuses on water suppliers in two sub-regions within the Los Angeles Basin – Los Angeles and Orange Counties. We included the cities of Long Beach, Newport Beach, Huntington Beach, Seal Beach and Costa Mesa in the Orange County sub-region, and the cities of Inglewood, Hawthorne, Torrance, Gardena and Lawndale in the West Los Angeles (LA) County sub-region (Figure 1). The residents in the West LA County sub-region (Hawthorne, Inglewood, Torrance) are supplied by public utilities, while Golden State Water Company Southwest serves customers in the cities of Gardena, Lawndale and parts of Inglewood. Residential water in the Orange County sub-region is provided by the cities of Huntington Beach, Long Beach, Newport Beach, Seal Beach, and Mesa Water District, which serves Costa Mesa and some communities in Newport Beach.

Los Angeles Department of Water and Power (LADWP), a large municipal utility in the region, serves a massive area (1200 km^2) and more than four million people.[39] We focused on those relatively smaller cities within the Los Angeles Basin that are served by independent water suppliers to minimize within sub-region heterogeneity in ecological and behavioral factors. Furthermore, the sub-regions that we included were selected because they encompass a large number of mosquito surveillance records before and during the drought period.

Urban water use data

We obtained data from SWRCB consisting of monthly total potable water production for each water supplier for the period of June 2014 through December 2019. These data were made available in response to drought emergency water conservation regulations[40], which mandated the State Water Board to report total water deliveries by all urban water suppliers that had more than 3000 connections, or among those supplying more than 3000 acre-feet of water annually. Urban water reductions of 25% were mandated nearly a year later by executive order (Apr 1, 2015), and were then slowly lifted, beginning with voluntary restrictions in February 2016 followed by fully lifting these restrictions in April 2017. Although statewide urban water reductions were mandated for up to 25%, in our study sub-regions the mandatory water reductions varied widely. For example, in the West LA County sub-region, the local water reductions ranged between 12 – 24 % (Inglewood and Golden State Water Company Southwest: 12%, Hawthorne: 16% and Torrance: 24%). In the Orange County sub-region, the restrictions were between 8 – 28% (Seal Beach: 8%, Long Beach: 16%, Huntington Beach and Mesa Water District: 20% and Newport Beach: 28%). Recycled water use was a small fraction of the total water use in our study sub-regions. The average percentage of recycled water in the West LA County sub-region was 12% and only cities of Inglewood and Torrance and Golden State Water Company Southwest reported use of recycled water. In the Orange County sub-region, the share of recycled water was also 12%, with reported use in Huntington Beach, Newport Beach, and Seal Beach. The SWRCB method of calculating monthly residential per capita water use, which we adopted, is:

$$residential\ per\ capita\ water\ use = \frac{total\ monthly\ water\ delivery \times \%\ residential\ use}{population}$$

Daily residential per capita water use was calculated for each water supplier and converted to liters.

Urban outdoor water use

We estimated outdoor water use from total residential water use following methods from Gleick *et al.*[9], and adopted by Mini *et al.*[11]. Because the data from SWRCB does not divide total residential water use between indoor and outdoor water use, we assumed that the lowest monthly per capita total residential water use in each calendar year (2014–2019) was equal to monthly indoor use for the year. We then estimated per capita outdoor water use by subtracting estimated indoor water use from the total residential water use for each month.

Income and household data

We determined the median household income and average household size of each city within the two study sub-regions using 2018, 1-year American Community Survey (ACS) data.[41] These data were included in order to assess whether there were regional differences in outdoor water use based on these socioeconomic characteristics.

Mosquito abundance data

We acquired mosquito surveillance data from the California Vector-borne Disease Surveillance System (CalSurv). We included adult female *Cx. quinquefasciatus* surveillance records collected from 2006–2016 within the two Los Angeles Basin sub-regions serviced by the Greater Los Angeles County Vector Control District, the Orange County Vector Control District, Los Angeles County West Vector Control District, and the Long Beach Vector Control Program. Only mosquito surveillance that was conducted with a CO_2 trap that was operated for a single night without malfunctioning was included (N= 5476 trap nights).

We developed two separate random forest model (ranger package in R 3.6.3) for each of the two study sub-regions. These models predicted the daily number of female *Cx. quinquefasciatus* captured in individual CO_2 traps at each CalSurv surveillance location using 104 climate, weather and land cover variables that were measured at daily, monthly and quarterly (average of three months) aggregations and lagged one to three time steps (Table 1). We included climate variables constituting gridded daily mean, minimum and maximum temperature and diurnal temperature variation (800 m pixel resolution), gridded total precipitation (4 km pixel resolution), and the ratio of total column soil moisture and total column anomaly as a proxy for drought status (~ 6 km pixel resolution). Land cover variables included elevation (10 m pixel resolution), vegetation canopy cover (30 m pixel resolution), vectorized extent of wetlands (delineated from greater than equal to 1:40,000 scale imagery) and impervious cover (30 m pixel resolution). Additionally, we included a categorical variable for city, dummy variables for each vector control agency that conducted trapping, as well as predictors for spatial (latitude, longitude) and temporal (month, year-week) features to account for unmeasured confounders[27] and an estimate of city-wide monthly and annual surveillance intensity as a proxy for mosquito control activities.

The models were trained with daily *Cx. quinquefasciatus* surveillance records collected from June through November from 2006 through 2013 (N= 3780 trap nights), a period that also included a major drought (2007–2009, 2012–2013). Each model consisted of an ensemble of 500 trees and was constructed using a spatio-temporal cross-validation scheme, in which one year of data and 5% of surveillance sites were iteratively withheld from the training of each tree. Out-of-sample model performance was then assessed by calculating r^2 of predictions that were made on records withheld from the training sample. This helped to reduce the risk of overfitting during training and ensured that out-of-sample predictions in new temporal and spatial domains would be robust.[42] We conducted a grid search to optimize several random forest hyperparameters, including the number of candidate predictors per split (mtry), the proportion of surveillance sites to remain out-of-bag in each tree, and the level of oversampling of years to correct sampling imbalances that affected performance. Node impurity was calculated using the estimated variance in the response variable, which is the default option for random forest regression in the ranger package. We used the trained random forest models to predict the number of female *Cx. quinquefasciatus* captured in CO_2 traps per trap night between June 2014 and November 2016 (N= 1693 trap nights), the core of the 2012–2016 drought that included the period of voluntary and mandatory water use restrictions.

Increasingly common in epidemiological analyses, counterfactual models are particularly advantageous in evaluating interventions that occurred once in a time series (n=1; e.g., a mass vaccination campaign), such that it is difficult to generate robust statistical inference on its effects without pseudo-replication.[43, 44] Our model predictions served as an estimate of host-seeking female *Cx. quinquefasciatus* abundance during the 2012–2016 drought under the counterfactual assumption that water use restrictions were not implemented. These predictions implicitly exclude the effects of water use restrictions, because the models were trained on surveillance records that were collected during drought (and non-drought) periods when such extensive residential water use restrictions were mandated.

We calculated a Pearson correlation coefficient (r) to compare the observed weekly average number of female *Cx. quinquefasciatus* captured per trap night in CO_2 traps (hereafter observed *Cx.* abundance) with predicted *Cx.* abundance within each study region. We compared predicted *Cx.* abundance in the two sub-regions with observed *Cx.* abundance during the voluntary and mandatory water restriction period to evaluate the counterfactual scenario of *Cx.* abundance without water use restrictions.

Results

Per capita residential daily water use for the Orange County sub-region was generally higher than the West LA County sub-region between June 2014 and December 2019 (Figure 2, S1, S2, Table 2; West LA County: 254.5 ± 2.9 liters (mean ± 1 standard error), vs Orange County: 301.2 ± 5.8 liters). For the same time period, average daily per capita *outdoor* water use for Orange County also exceeded that of West LA County (West LA County: 44.9 ±

2.9 liters, vs Orange County: 79.0 ± 5.5 liters). Residential water use followed a seasonal cycle, with peaks in the summer (June - August) and declines in the autumn (September - November) in both study regions (Figure 2a, 2b). The per capita residential daily water use from January 2015 to December 2019 for the South Coast region of Southern California, which included both study sub-regions was about 82 gallons (~ 310 liters).

In the period between June 2014 and March 2015, before mandatory water restrictions were enacted, the water use in both regions was higher than the average per capita residential water use over the period between June 2014 and December 2019, despite the onset of drought in 2012. For example, per capita residential daily water use between June 2014 and March 2015 in West LA County was 271.3 ± 8.1 liters (outdoor water use: 54.8 ± 8.7 liters), compared with 320.5 ± 19.0 liters (outdoor water use: 90.1 ± 16.4 liters) in Orange County. Both study sub-regions reduced their water use during the drought between 2014 and 2016 relative to the 2013 baseline—average per capita residential daily water use in West LA County was reduced by 1.9% in 2014, 9.7% in 2015 and 9.5% in 2016 (Figure 2c, Table 2). During voluntary and mandatory water use drought restrictions, Orange County achieved greater reductions in average per capita residential daily water use relative to 2013 levels, falling 3.8% in 2014, 13.9% in 2015, and 15.1% in 2016 (Figure 2c, Table 2). During the period of mandatory water use restrictions (April 2015 - February 2016), average per capita residential daily water use decreased (average percent decrease: 12 % in West LA County; 17 % in Orange County) in both West LA County (total residential: 253.3 ± 4.3 liters; outdoor: 33.5 ± 4.2 liters) and Orange County (total residential: 265.2 ± 9.5 liters; outdoor: 58.5 ± 9.1 liters).

After mandatory water use restrictions were lifted in February 2016, during the period of voluntary water use restrictions (until April 2017) water use started to rebound in Orange County and was slightly higher than the long-term (2014–2019) average water use (total residential: 284.8 ± 13.5 liters; outdoor: 79.5 ± 14.2 liters), and approximately equivalent to the long-term (2014–2019) average water use in West LA County (total residential: 246.3 ± 5.7 liters; outdoor: 33.1 ± 4.6 liters). Even though average per capita residential daily water use increased in Orange County, it remained lower than the 2013 baseline (Table 2). During the period of water use restrictions, a total of 709 warnings and zero penalties were issued in West LA County, while in Orange County, 18,569 warnings and 2,256 penalties were levied. The median household income was higher for cities in Orange County ($88,000 in 2018) compared to West LA County ($62,500 in 2018). The average household size in West LA County was bigger than cities in Orange County sub-region (West LA County: 2.9, vs Orange County: 2.6).

A modest degree of correspondence was observed ($r^2 = 0.31$ for West LA County; $r^2 = 0.51$ for Orange County) between random forest model predicted *Cx.* abundance and surveillance observations during the model training period between 2006 and 2013 (Table S1), before formal water use restrictions were in place. From a total of 104 climate, weather and land cover variables (Table 1), we only reported the permutation importance of top 10 environmental predictors of which elevation, impervious cover and temperature (minimum temperature, diurnal variation of temperature, maximum and mean temperature) were important predictors in both study sub-regions (Figure S3).

We compared weekly average observed and predicted *Cx.* abundance for four time periods: 1) a pre-drought period (2010–2011); 2) the drought period without water restrictions (2012–2013); 3) the drought period with voluntary water use restrictions (2014 and 2016); and 4) the drought period with mandatory water use restrictions (2015) (Figure 3, Table S2). Between 2010 and 2011 (pre-drought period), substantial correlation was observed between average weekly observed and predicted *Cx.* abundance (West LA County Pearson correlation coefficient, r=0.83, $p < 0.001$; Orange County r=0.88, $p < 0.001$; Figure 3). Model predictions continued to strongly correspond with observed *Cx.* abundance during the first years of the drought prior to the implementation of outdoor residential water use restrictions (West LA County r=0.72, $p < 0.001$; Orange County r=0.88, $p < 0.001$), but started to weaken during periods of voluntary water use restrictions in 2014 and 2016 (West LA County r=0.62, $p < 0.001$; Orange County r=0.76, $p < 0.001$). The lowest correlation between average weekly observed and predicted *Cx.* abundance was during the period of mandatory water use restrictions (West LA County r=0.58, $p < 0.001$; Orange County r=0.70, $p < 0.001$).

We evaluated the effects of voluntary (2014 and 2016) and mandatory (2015) water use restrictions on *Cx.* abundance by comparing observed and counterfactual predictions of *Cx.* abundance. Because our model did not account for water use restrictions, counterfactual predictions anticipated higher *Cx.* abundance than was observed during this period (Figure 4). We estimate that had *voluntary* water use restrictions not been implemented, average *Cx.* abundance in West LA and Orange County would have been 28 ± 8 % and 31 ± 4 % higher respectively (expressed as mean percent difference between predicted and observed *Cx.* abundance ± standard error; see Figure 4). If *mandatory* water use restrictions were not in place, we estimate that average *Cx.* abundance in West LA and Orange County would have been 61 ± 13 % and 52 ± 6 % higher respectively (Figure 4). Though the counterfactual model does slightly overpredict *Cx.* abundance even prior to the drought period (2010–2011), the difference was only 17 ± 7 % and 13 ± 4 % in West LA and Orange County respectively. During the drought period without water use restrictions (2012–2013), the difference between predicted and observed *Cx.* abundance was WLA 27 ± 7 % in West LA County and OC 31 ± 3 % in Orange County. We accounted for overfitting during the pre-drought period by subtracting the mean percent difference between predicted and observed *Cx.* abundance during the pre-drought period with the mean percent difference between predicted and observed *Cx.* abundance during the drought with voluntary and mandatory restrictions. Our model estimates that voluntary water use restrictions were not effective in contrast to drought without restrictions in reducing *Cx.* abundance (Figure 4). Our counterfactual model (bias corrected) estimates that without mandatory water use restrictions, *Cx.* abundance on average would have been 44% and 39% higher in the West LA County and Orange County sub-regions respectively.

Discussion

Our results show that both the West LA and Orange County sub-regions reduced their water use when water use restrictions were introduced. These reductions likely contributed to significant decreases in *Cx.* abundance. Our results show that both the West LA and Orange County sub-regions reduced their water use when water use restrictions were introduced.

These reductions, especially during the mandatory water use restrictions period, likely contributed to significant decreases in *Cx.* abundance. Our bias corrected counterfactual model estimates that without mandatory water use restrictions during 2015, *Cx.* abundance on average would have been 44 % and 39 % higher in the West LA County and Orange County study sub-regions respectively, which could contribute to an increase in enzootic or epizootic WNV transmission. These findings suggest that mandatory water use restrictions in California, and potentially other regions with Mediterranean climates characterized by dry summer and wet winter months can contribute to reductions in the abundance of *Cx. quinquefasciatus*.

Water use restrictions mandated by the State of California appear to have stemmed these potential increases, a finding that is consistent with previous studies showing that voluntary and mandatory restrictions on outdoor irrigation significantly reduced per capita water usage within the LADWP service area from 1985–1992 and 2006–2010.[11, 45, 46] Despite overall reductions, water use restrictions had varying effects across our study sub-regions, with pronounced decreases in usage in West LA County relative to Orange County. Differences in compliance could explain the sub-regional variation. Authorities in the more affluent Orange County sub-region issued 0.21 warnings per capita and 0.03 penalties per capita compared to just 0.006 warnings per capita and zero penalties in West LA County sub-region. It is likely that strict enforcement of water use restrictions acts as deterrent to water use during restriction periods.

Socioeconomic conditions may have contributed to differences in water use and compliance to restrictions among the subregions. For example, Mini *et al.* [47] found a statistically significant, positive correlation between residential water use and median household income in neighborhoods served by the Los Angeles Department of Water and Power (LADWP), and Mini *et al.* [11] showed that water use restrictions were less effective in higher income residential neighborhoods served by the LADWP. Palazzo *et al.* [48] also found that higher median household income was associated with lower compliance of water use restriction in California during the 2012–2016 drought. Higher median household incomes for cities in Orange County ($88,000 in 2018) compared to West LA County ($62,500 in 2018) may have contributed to non-compliance and could explain why *Cx.* abundance during the period of mandatory water use restrictions did not decline as extensively in the Orange County subregion. Work by Harrigan *et al.* [22] suggests that socio-economic conditions (e.g., per capita household income) may in fact be a stronger predictor of mosquito abundance and WNV incidence in Orange County than other environmental variables such as temperature and rainfall. Thus, drought, without mandatory water use restrictions, may counterintuitively *increase* the availability of larval habitats for vectors in naturally dry, highly irrigated settings, particularly in wealthy areas.

During the drought, average residential per capita daily water use in California would likely have increased had it not been for the intervention by the SWRCB, based on the behavior during prior drought periods. For instance, higher temperatures and reduced precipitation increased residential water use in neighborhoods served by the LADWP between 2000–2010,[11, 47] and in Phoenix, AZ between 1995–2004.[49] In these settings, an increase in evapotranspiration from urban lawns—and residents' purported desire to maintain green lawns during dry and warm summer months—combined with inefficiency in urban lawn irrigation resulted in increased outdoor water use.[49, 50]

Although our results indicate that mandatory water use restrictions are an effective means of reducing water use and limiting vector abundance during drought, alternative and potentially more sustainable methods are also available during both drought and non-drought periods. One such avenue, proposed by Governor Jerry Brown during the drought in 2015, would be to replace 50 million square feet of lawns throughout the state with drought tolerant landscaping. Adoption of such measures would then decrease the per capita daily residential outdoor water use (permanently) and limit the availability of surface water in irrigated lawns that could support mosquito larval development. Additional measures to better manage urban water sources in an increasingly water-limited future include higher water pricing,[11, 47] incentivizing turf grass replacement,[12, 51, 52] increasing drought saliency with high media attention,[53] landscaping innovation such as adding trees next to irrigated lawns to minimize evapotranspiration losses,[54] irrigating with recycled water,[55] and strict restrictions on irrigation frequency.[47, 56, 57] Additionally, green infrastructure, such as bioretention systems like bioswales and vegetation strips that infiltrate runoff, can also be used to limit the persistence of surface water that could support mosquitoes.[36] Such infrastructure rarely contains mosquitoes—a study in California indicated that less than 5% of green stormwater infrastructure contained larval mosquitoes, and those that did were easily modified to reduce standing water and eliminate mosquitoes entirely.[36] Although replacement of turf grass with drought resilient vegetation would lower outdoor water use and limit the availability of aquatic habitats needed for larval development, adoption of recycled water for outdoor residential water use could support increased mosquito abundance[58] because of higher nutrient concentration in recycled water.[59] However, a study in Pacifica, CA, found that mosquito abundance was reduced downstream from an outlet with recycled water when compared with mosquito abundance above the outlet.[60]

Future hydroclimatic conditions in Southern California are likely to include increased variability in both interannual and intraseasonal precipitation, often fluctuating between very dry and very wet conditions.[5] Historically, the coastal part of the Los Angeles Basin experiences fewer than 10 days per year of hot days—defined as days with temperature equal to, or greater than, 35°C—but under the Representative Concentration Pathways (RCP) 8.5 climate scenario, by the end of the century the region is projected to experience 37 hot days per year.[61] Though regional efficiency in per capita water use has improved in the last few decades,[62] increasingly warm and dry conditions may make additional water use savings during droughts in the Los Angeles Basin extremely challenging.[2] Under future scenarios of a volatile climate in the region,[5] it is unlikely that current levels of irrigation will be sufficient to sustain healthy urban vegetation in its current form during periods of drought.[55, 63] In the coming decades, water restrictions, replacement of lawns with drought tolerant vegetation and the creation of green infrastructure will serve an increasingly essential role in the maintenance of adequate water supplies and reduction in the risk of transmission of vector-borne diseases.

This study had several limitations. First, we observed that water use increased in Orange County, a phenomenon known as “rebounding”,[64, 65] but we could not evaluate the effects on *Cx.* abundance owing to a lack of vector surveillance data during the rebound period. Further research is needed to determine whether rebounds in water usage contributed to increases in vector abundance during the post-restriction period. Also, we were unable to directly account for mosquito control activities in the region. Within our two study sub-regions, residents in high income neighborhoods are likely to support more extensive mosquito eradication programs[22] which could lead to a decrease in mosquito abundance. Many vector control districts in the Los Angeles Basin routinely apply pesticides to eradicate adult and larval mosquitoes yet records of these activities are not widely available. We attempted to account for this by including the intensity of mosquito surveillance, a proxy for control activities, as a predictor in the random forest models.

In this study, we examined the role of outdoor water use restrictions on *Cx.* abundance during the 2012–2016 California drought, comparing predicted *Cx.* abundance if water restrictions had not been implemented with mosquito surveillance data collected during that period. We found that state mandated water use restrictions during the 2012–2016 California drought reduced both total residential and outdoor water use and were associated with lower *Cx.* abundance in two urban counties in the Los Angeles Basin. Mandatory water use restrictions were more effective compared to voluntary water use restrictions at reducing *Cx.* abundance by 44% in West LA County and by 39% in Orange County sub-regions. Because future climate projections forecast an increase in hydrologic extremes and warmer temperatures, implementation of water use policies that limit residential and outdoor water use will ensure sustainable access to water resources and may have the added benefit of reducing mosquito abundance and the transmission of mosquito-borne pathogens, such as WNV, to humans.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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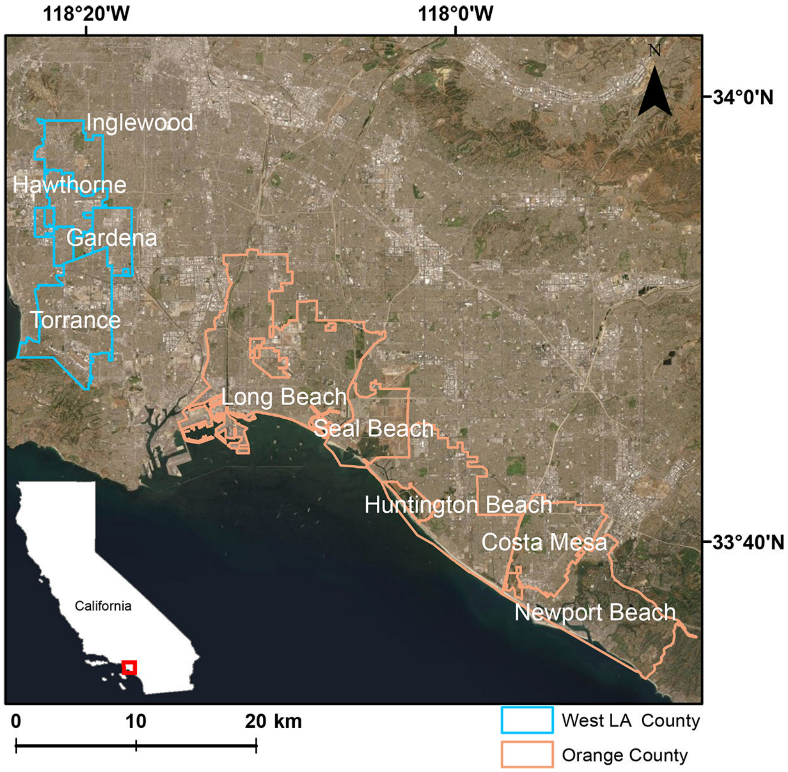

Figure 1:

The two sub-regions in the Los Angeles Basin (West LA County and Orange County).

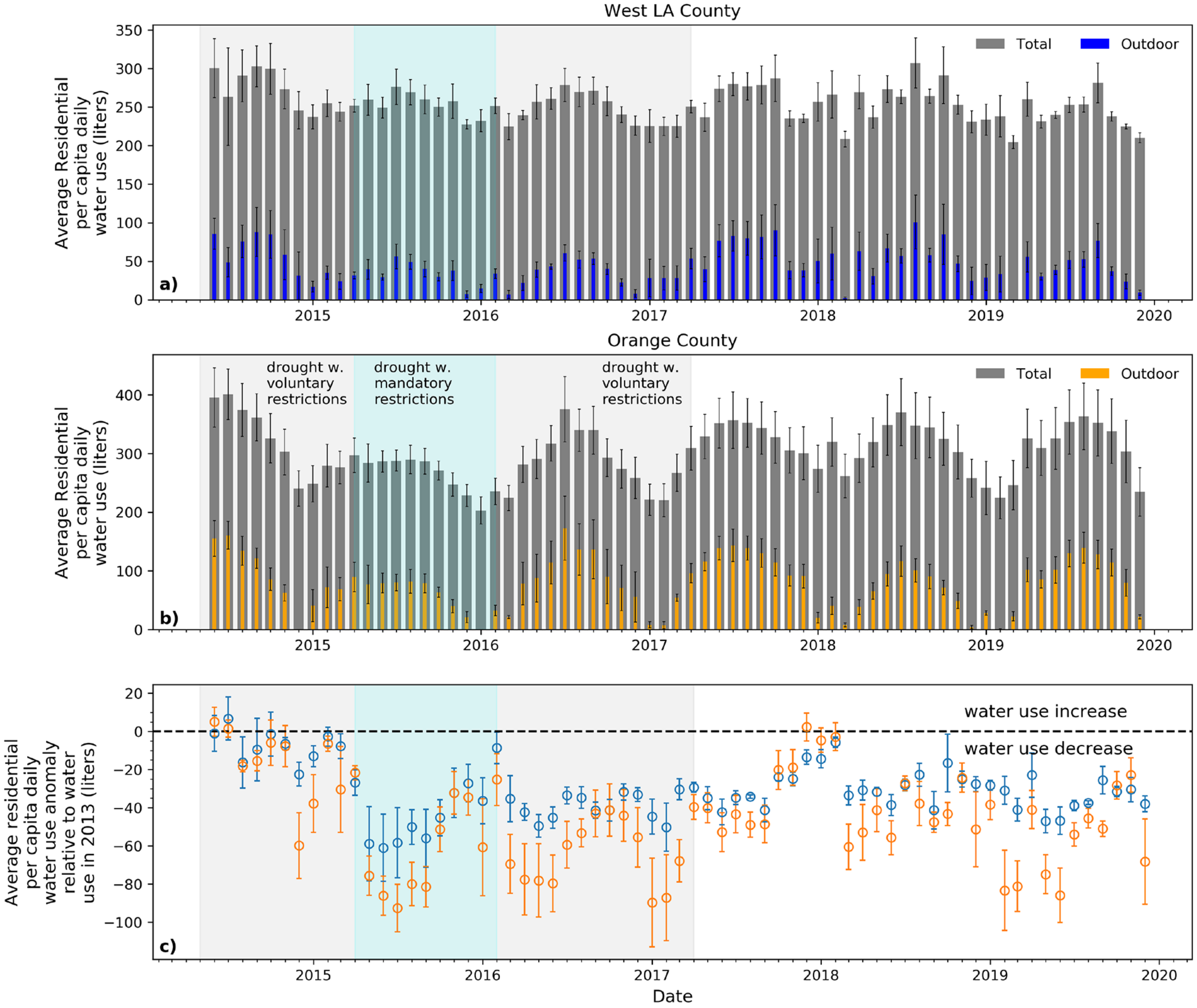

Figure 2:

The time series of average (± standard error) residential daily per capita water use, and average outdoor residential daily per capita water use in West LA County (a) and Orange County (b). The percent water use reduction in each month relative to the monthly water deliveries in 2013 (c). The shaded time periods represent drought with voluntary water use restrictions (2014 and 2016) and drought with mandatory water use restrictions (2015).

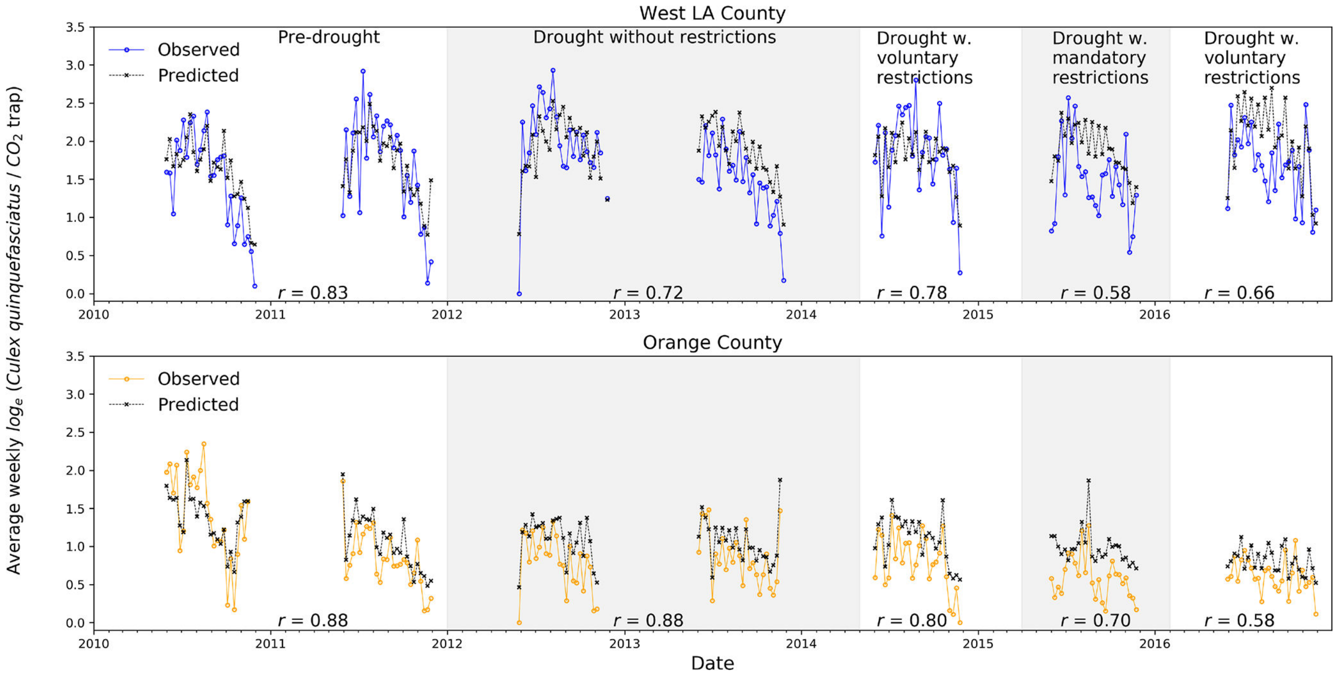

Figure 3:

Model-predicted *Cx.* abundance versus observed *Cx.* abundance in West LA County (a), and Orange County (b). Model predictions of *Cx.* abundance (black) in both study sub-regions implicitly exclude the effects of water use restrictions between April 2014 and November 2016. *r* is the Pearson correlation coefficient for each time period.

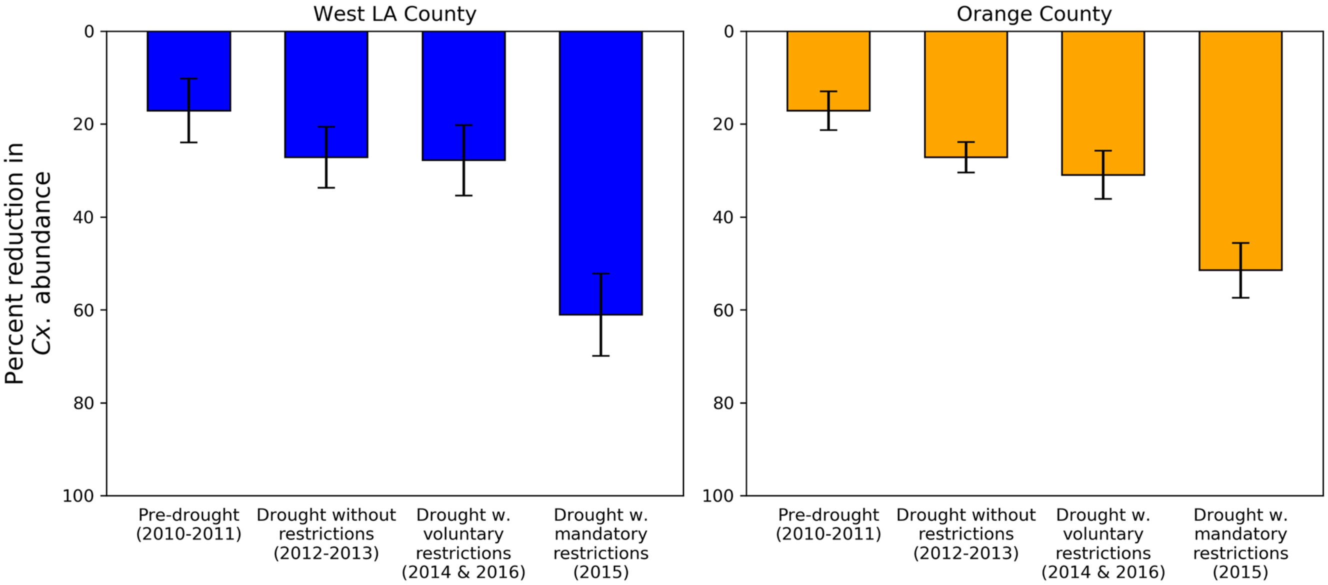

Figure 4:

The percent reduction in *Cx.* abundance ((predicted *Cx.* abundance - observed *Cx.* abundance) / observed *Cx.* abundance * 100) in West LA County (a) and Orange County (b) during periods of pre-drought (2010–2011), drought without water use restrictions (2012–2013), and drought with voluntary (2014 and 2016) and mandatory (2015) water use restrictions.

Table 1:

Predictor variables in random forest model predicting *Cx.* abundance. Adapted from Skaff *et al.*[27]

Model Predictors	Spatial Resolution	Temporal Resolution	Data Source
Climate (3 lags at daily, weekly, monthly, quarterly aggregations)			
Mean Temperature	800m	Daily	TopoWX
Minimum Temperature	800m	Daily	TopoWX
Maximum Temperature	800m	Daily	TopoWX
Diurnal Variation	800m	Daily	TopoWX
Total Precipitation	4km	Daily	PRISM
Drought (total column soil moisture/total column anomaly)	~6km	Daily	Variable Infiltration Capacity (VIC) Model
Land-cover (quantified within 10, 100, 1000m buffers)			
Palustrine and Riverine Wetland	Vector	—	National Wetlands Inventory (NWI)
Impervious surfaces	30m	—	National Land Cover Dataset (NLCD)
Canopy cover	30m	—	USGS Global Tree Canopy Cover
Elevation	10m	—	National Elevation Dataset (NED)
Non-Environmental Predictors			
Trap Latitude	—	—	—
Trap Longitude	—	—	—
City	—	—	—
Month	—	—	—
Week of Year	—	—	—
Vector Control Agency	—	—	California Vectorborne Disease Surveillance System

Table 2:

Average residential and outdoor per capita water use (liters, with ± standard error) for two study sub-regions in California. The average percent reduction is calculated by subtracting the monthly daily per capita water use from the baseline year, 2013.

Year	Average residential per capita water use (liters)	Average outdoor per capita water use (liters)	Total water use reduction relative to 2013 (%)
West LA County			
2014	282.4 ± 35.1	67.4 ± 26.6	1.89
2015	253.2 ± 15.4	33.0 ± 8.7	9.66
2016	250.9 ± 15.3	32.9 ± 77.1	9.52
2017	252.6 ± 17.1	55.3 ± 19.1	8.90
2018	260.2 ± 19.4	53.7 ± 198	6.95
2019	239.1 ± 12.6	36.4 ± 11.0	9.21
Orange County			
2014	343.0 ± 41.4	102.8 ± 184	3.78
2015	273.5 ± 24.5	66.0 ± 19.7	13.87
2016	286.0 ± 32.9	83.0 ± 33.4	15.12
2017	307.0 ± 38.7	94.2 ± 16.9	12.21
2018	313.5 ± 45.2	58.2 ± 14.1	9.88
2019	301.4 ± 49.2	79.4 ± 16.1	14.85