1   Household and climate factors influence *Aedes aegypti* risk in the arid city of Huaquillas,

2   Ecuador

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Abstract

Arboviruses transmitted by *Aedes aegypti* (e.g., dengue, chikungunya, Zika) are of major public health concern on the arid coastal border of Ecuador and Peru. This high transit border is a critical disease surveillance site due to human movement-associated risk of transmission. Local level studies are thus integral to capturing the dynamics and distribution of vector populations and social-ecological drivers of risk, to inform targeted public health interventions. Our study examines factors associated with household-level *Ae. aegypti* presence in Huaquillas, Ecuador, while accounting for spatial and temporal effects. From January to May of 2017, adult mosquitoes were collected from a cohort of households (n = 63) in clusters (n = 10), across the city of Huaquillas, using aspirator backpacks. Household surveys describing housing conditions, demographics, economics, travel, disease prevention, and city services were conducted by local enumerators. This study was conducted during the normal arbovirus transmission season (January - May), but during an exceptionally dry year. Household level *Ae. aegypti* presence peaked in February, and counts were highest in weeks with high temperatures and a week after increased rainfall. Presence of *Ae. aegypti* was highly variable between clusters. Hierarchical generalized linear models were used to explore household social-ecological variables and female *Ae. aegypti* presence. Houses with *Ae. aegypti* used larvicide in water tanks and had high awareness of dengue transmission. We found that homes were more likely to have *Ae. aegypti* when heads of household had lived in the neighborhoods for longer than average (>22 years), when households had more occupants than average (>4.5), had a female head of household, and received more frequent garbage collection. *Ae. aegypti* presence was less likely in households with reliable water supply and septic systems. Based on our findings, infrastructure access, urban

48   occupancy patterns, and seasonal climate are important considerations for vector control in this

49   city, and even in dry years, this arid environment supports *Ae. aegypti* breeding habitat.

50

51   **Author summary**

52   Mosquito transmitted infectious diseases are a growing concern around the world. The yellow

53   fever mosquito (*Aedes aegypti*) has been responsible for recent major outbreaks of disease,

54   including dengue fever and Zika. This mosquito prefers to bite humans and lay its eggs in

55   artificial containers such as water tanks and planters. This makes *Ae. aegypti* well suited to

56   become established in growing urban areas. Controlling these mosquitoes has been an important

57   way to reduce the risk of disease transmission. Studies that are undertaken to understand local

58   factors that contribute to the continued survival of the mosquito can be used to inform control

59   practices. We conducted a study in the largest city on the border of Ecuador and Peru where we

60   collected adult mosquitoes from houses and surveyed household members about their behaviors,

61   perceptions, and housing infrastructure associated with the mosquito vector. Mosquitoes were

62   most numerous in weeks with high temperatures and a week after increased rainfall. Larvicide

63   was a commonly used control strategy in homes where *Ae. aegypti* was present. We found that

64   houses that had more people, female heads of household, heads of household that had lived in the

65   neighborhood for a long time, and had unreliable water service, were more likely have

66   mosquitoes present, while houses that used septic systems were less likely to have mosquitoes

67   present.

Introduction

Arboviral diseases are an increasing global concern [1]; dengue fever has the largest health burden, with 58.4 million cases reported annually worldwide [2]. The *Aedes aegypti* (*Ae. aegypti*) mosquito is the primary vector of dengue virus and other important arboviruses such as chikungunya, yellow fever, and Zika [1,3]. This mosquito is well-adapted to urban environments as it is an anthropophilic container breeder [4]. Increasing urbanization and trends in international trade and travel have greatly facilitated the spread and establishment of *Ae. aegypti* and the diseases it transmits [5]. Vector control remains the primary strategy to prevent arboviral diseases [6], and it has become increasingly apparent that the social and ecological factors that influence vector populations vary greatly in space and time [7,8]. This has significant implications for the effectiveness of vector control programs. Local studies are therefore necessary to assess place-specific drivers and to inform interventions [9]. *Ae. aegypti* mosquitoes are sensitive to abiotic factors such as climate, including temperature, rainfall and relative humidity [10]. Its anthropophilic nature also makes the mosquito sensitive to human activities [11] such as household water storage or use of repellant. Thus, it is important to examine both the social and ecological components of a local environment to understand sub-city risks of vector presence, and the potential for intervention.

International border regions represent an interesting opportunity for the study of disease vectors. Neighboring countries may be a source of infected vectors or imported human cases of disease [12]. Differences in environment, socio-economic status, access to healthcare, healthcare practices, and vector control practices between countries can impact the burden of disease, abundance of vectors, and infection levels of vectors [12,13]. Historically, international transportation of goods and people has introduced or re-introduced *Ae. aegypti*, *Aedes albopictus*

91   (a secondary vector of dengue) and dengue virus to new locations [14–16]. Cities along borders

92   may also have high levels of migrant populations or may be a through-way for migrating

93   populations, who can serve as reservoirs of vector-borne disease [17,18].

94   Ecuador has a history of high arboviral disease burden [19,20]. Yellow fever dominated

95   during early 20th century, and dengue fever emerged as the principal mosquito-borne disease at

96   the beginning of the 21st century with the decline in malaria cases [21,22]. More recently, the

97   introduction of new viruses, such as chikungunya and Zika, has resulted in major epidemics [23].

98   There have been multiple studies in recent years of climate, social-ecological factors, and *Ae.*

99   *aegypti* in Ecuador [11,19,24–29]. These neighborhood-level studies have primarily focused on

100   Machala, Ecuador, an urban center with a steppe climate (BSh) per the Köppen climate

101   classification system (e.g., intermediate between desert and humid climate). Studies found that

102   both climate and social-ecological factors influenced the presence of immature and adult *Ae.*

103   *aegypti* in neighborhoods [11,24–29]. The El Niño–Southern Oscillation is an important driver of

104   the climates of southern Ecuador and northern Peru [27]. To date, there have been no studies of

105   the impacts of climate and social-ecological system (SES) on *Ae. aegypti* in the desert climates

106   of Ecuador, nor along border regions.

107   This study aims to identify the climatic and social-ecological aspects of household-level

108   *Ae. aegypti* presence in the arid border city of Huaquillas. These insights can lead to a better

109   understanding of how this vector-borne disease system functions and where potential levers of

110   control might be found. The knowledge gained can help inform intervention decisions in

111   Huaquillas and other similar settings. Additionally, this study, in combination with similar local-

112   scale studies in the region, can help answer questions relating to scale and heterogeneity in

113   arboviral disease systems.

114

Methods

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Ethical review

118 This study protocol was reviewed and approved by Institutional Review Boards (IRBs) at SUNY

119 Upstate University, the Luis Vernaza hospital in Guayaquil, Ecuador, and the Ministry of Health

120 of Ecuador. Prior to the start of the study, adult participants ($\geq$ 18 years of age) engaged in a

121 written informed consent (conducted in Spanish). To protect the privacy of participants, data

122 were de-identified prior to use in any of the analyses conducted in this study.

123

Study site

125 Huaquillas is a coastal city in southern Ecuador with a population of 48,285 (Fig 1) [30]. It is

126 situated on the border of Ecuador and Peru and is the primary crossing at the southern border,

127 and a major hub of transit between the two countries [31]. In terms of total migration, Huaquillas

128 is the third most active city in Ecuador, with 622,405 arrivals and departures annually [31]. There

129 is frequent economic exchange with the similarly-sized Peruvian city of Zarumilla located less

130 than 2 km from the border [32,33]. Increased binational cooperation and a relaxation of trade and

131 travel barriers in recent decades has contributed to increased urban development on both sides of
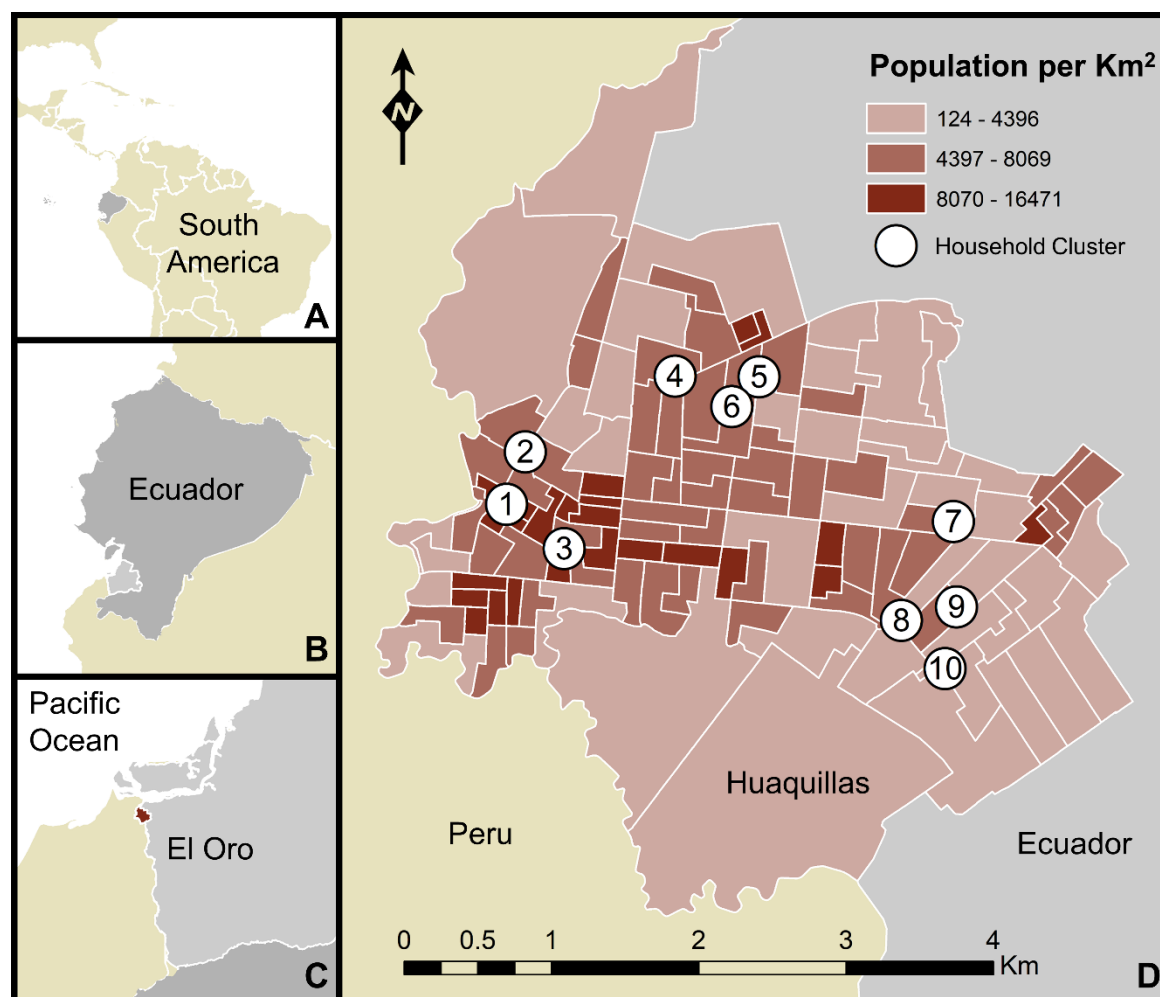
132 the border [33].

Fig 1. Map of the study area. Huaquillas is located within South America, Ecuador, and El Oro province. The map includes household cluster locations where sampling took place (white circles denote areas where up to 5 houses were sampled, but precise household locations are not shown, to protect identities) and the population density of Huaquillas at the census tract level. a) location of Ecuador, b) location of El Oro province, c) location of Huaquillas (red) d) Huaquillas population and sampling sites.

Huaquillas is in a low-lying coastal region highly suitable for *Ae. aegypti*, as underscored by

major outbreaks of dengue fever in recent years [27]. It has a hot desert climate (BWh) per the

the Köppen climate classification system [34]. While desert climates are often characterized by

limited precipitation, intense sunlight, and little vegetation, actual conditions can vary greatly by

place. Huaquillas experiences a monsoon season which occurs during the first half of the year,

7

146   with monthly total rainfall peaking in February at 128 mm (Fig 2). Increased precipitation

147   coincides with high temperatures. Annual mean temperature ranges from 21.6-27.6°C. Minimum

148   daily temperatures range from 18.8—22.3°C annually and maximum daily temperatures range

149   from 25.8—33.0°C annually.

150

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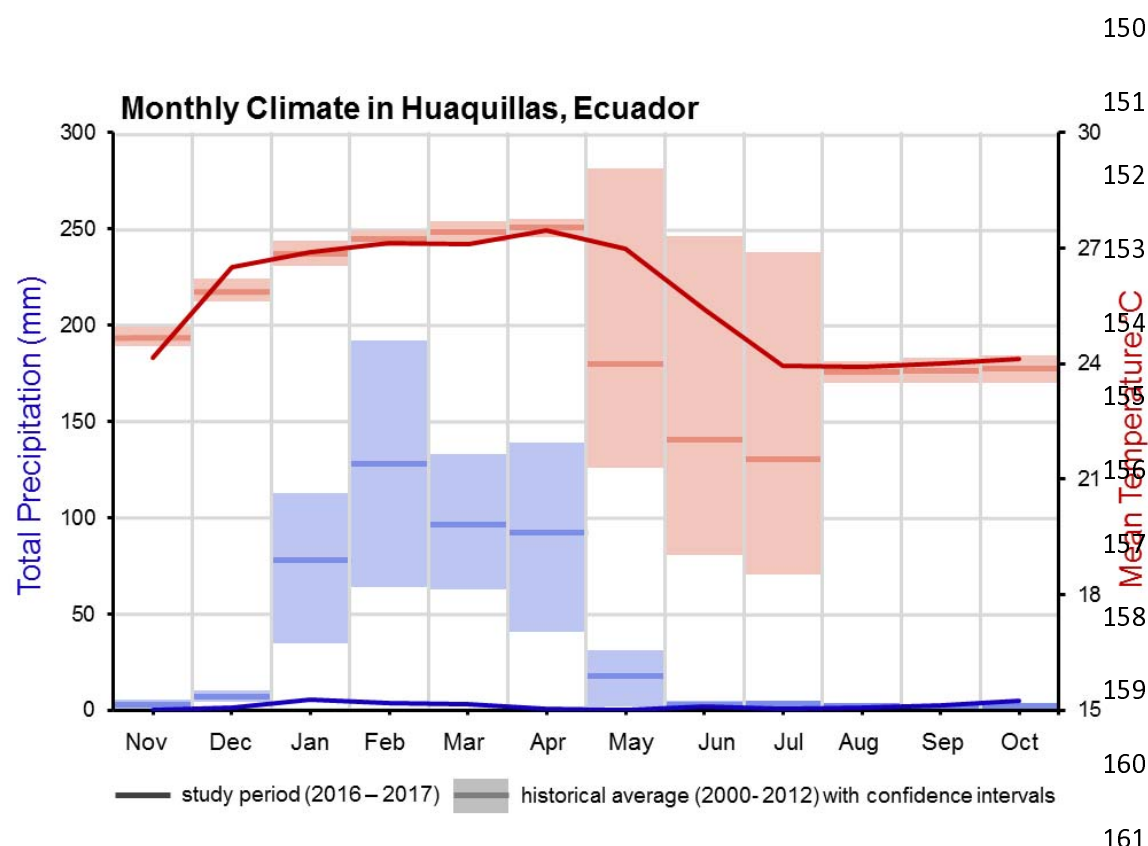
162   **Fig 2. Climate in Huaquillas, Ecuador.** Monthly mean temperature in red and total monthly
163   precipitation as blue. Solid lines represent the climate during the study period (2016-2017) while
164   box plots represent the climatology from 2000-2012 (historical monthly averages and 95%
165   confidence intervals).
166
167   **Data sources**

168   *Climate data*

169   The National Institute of Meteorology and Hydrology (INAMHI) provided daily climate data for

170   Huaquillas from 2000—2012 and hourly data (March 2016—December 2017) from an automatic

171   weather station in the city. Both datasets include minimum, maximum, and mean temperature,

172   and total daily precipitation.

173   *Census data*

174   Tract-level census data from the most recent national census (2010) was provided by the

175   National Institute of Statistics and Census (INEC) and were assigned to georeferenced tract

176   polygons were provided by INAMHI.

177

178   *Participating households*

179   Households were selected for inclusion in this study using a semi-random selection process

180   (cluster design). The study was designed to capture clusters of up to five households facing

181   similar risks within the radius of the flight range of an *Ae. aegypti* mosquito. Each cluster

182   included a central household with four or five nearby households, preferably within a 250 m

183   radius to represent the flight distance of *Ae. aegypti* [35]. 10 clusters were located across the city.

184   The resulting sampling design was a favorable balance between sufficiently accounting for the

185   heterogeneity of the Huaquillas urban environment and the logistical feasibility of regularly

186   visiting the households. Houses were georeferenced and given specific house and cluster codes.

187

188   *Household mosquito samples*

189   Adult mosquitoes were collected from households biweekly during January—May 2017, using

190   backpack aspirators. Not all clusters were sampled in each sampling event, for logistical reasons.

191   Adult mosquitoes were stored on ice in a cooler and were transported to the entomology lab at

192   the Universidad Técnica de Machala, Ecuador, 74km by vehicle. Specimens were enumerated

193   and sorted by sex and species (*Ae. aegypti* and other).

194

195 *Household surveys*

196 The head of each household responded to a survey about household demographics, occupation,

197 access to public services, knowledge and perceptions of mosquito-borne disease, mosquito

198 control and prevention, and household expenditures [36]. Study personnel completed a visual

199 assessment of housing conditions, as in previous studies in the region [11,36]. Together, these

200 responses comprise the social-ecological system (SES) variables available for analyses.

201

202 **Data Analyses**

203 All data processing and analyses were conducted in R version 3.5.1 [37] using the packages

204 "rgdal" [38], "betareg" [39,40], "lrtest" [41], "lme4" [42], "glmulti" [43] and "MuMIn" [44].

205

206 *Climate data*

207 Daily climate data from 2000-2012 were aggregated to month by summing precipitation readings

208 and averaging minimum, maximum, and mean temperatures. A long-term monthly mean of each

209 variable was calculated and 95% confidence intervals were constructed using an ordinary

210 bootstrap procedure with 1000 replicates [45,46]. These long-term data served as the baseline for

211 examining the monthly climate of Huaquillas in 2017.

212 Hourly climate data from 2016 and 2017 were aggregated to weekly measures. Hourly

213 precipitation readings during that period were summed for weekly precipitation. Hourly

214 temperature data were used to derive daily mean, minimum, and maximum temperatures.

215

216 *Household mosquito samples*

217 Household *Ae. aegypti* counts were summarized as presence: sampling events were classified as

218 "positive" if female *Ae. aegypti* mosquitoes were present, and the proportion of positive

219 households was calculated for each week. Household mosquito sampling occurred at 2 or 3 week

220 intervals, so *Aedes aegypti* presence data were discontinuous [47]. Cross correlations using

221 Pearson's r were calculated for *Ae. aegypti* presence and climate variables (precipitation, mean,

222 maximum, and minimum temperature) lagged from 0 to 6 weeks, with statistical significance

223 assessed using t-tests. Statistically significant climate indicators were used to construct a beta

224 regression model to capture the relationship between climate and positive households, and multi-

225 model selection used to derive the best-fit model of these climate factors, using the package

226 "glmulti" in R, and "MuMin" to create a weighted model average between models falling within

227 2 AICc of the minimum (top model).

228

229 *Assessing temporal and spatial signals*

230 To assess whether there was a temporal signal in household-level presence of female *Ae. aegypti*

231 in the study group, at a monthly scale, only households with sampling events in all months were

232 included. For each household, if multiple collections occurred in a month, one collection record

233 was randomly selected to represent *Ae. aegypti* presence in that month.

234 To assess whether there was a spatial signal among the clusters of households in the

235 study, for months and then clusters, the proportion of households with *Ae. aegypti* was

236 calculated, and 95% binomial confidence intervals were derived using the Wilson score interval

237 [48]. Pearson's chi-squared tests were used to assess differences in *Ae. aegypti* presence between

238 months and between clusters. Fisher's exact test was used as a post hoc analysis to assess which

239 groups were significantly different from one another. To reduce the chance of observing spurious

11

240 differences between groups, which often occurs when conducting multiple comparisons on a set

241 of data, p-values were adjusted using the false discovery rate method [49].

242

243 *Bivariate tests for social factors*

244 Associations between survey responses and household female *Ae. aegypti* presence during the

245 study period were measured using bivariate tests. Questions that addressed social-ecological

246 factors hypothesized to be important for vector population dynamics at this study site (based on

247 previous studies in this region) were selected from the full household survey for analysis

248 [11,25,36,50]. Hypothesized factors included water storage practices, building materials, and

249 economic status. Questions that had a low rate of response were excluded to minimize

250 observations discarded due to missing data. Questions that had the same response for nearly

251 every observation were also excluded because they offer little ability to differentiate between

252 houses with and without *Ae. aegypti*. Bivariate statistical tests were used assess to differences in

253 survey responses by *Ae. aegypti* presence (Fisher's exact test for binary responses and t-tests for

254 numerical responses). These tests did not consider the month of each mosquito sample event.

255

256 *Social-ecological system (SES) models of household factors and Aedes aegypti presence*

257 Data inclusion criteria for the SES models were the most stringent. Households were required to

258 have mosquito samples in all months; those with more than one sampling event per month had

259 one event randomly selected for inclusion.

260 Using an information-theoretical approach, competing models of household female *Ae.*

261 *aegypti* presence as a function of SES variables found to be significant in bivariate analyses were

262 constructed using the 'dredge' function in package "MuMin" in R. Using Akaike's Information

12

263   Criterion corrected for small sample size (AICc) [51], an exhaustive search of all possible

264   combinations of SES variables was conducted. The top model had the lowest AICc score, and

265   competing models were within two AICc points of the top model. The relative importance of

266   each variable in the top and competing models was assessed using summed Akaike weights,

267   which considers both the frequency a variable appears in the models, as well as the performance

268   of these models [44,52]. All models included random effects of cluster and month to account for

269   the unobserved differences between groups of observations [53]. We created a weighted average

270   model of all models within 2 AICc points of the top model.

271

272   **Results**

273   Sixty-three households participated in the study. Fifty-eight heads of household (HOHs) (92%)

274   responded to the survey. The average distance between households within clusters was 86 m. A

275   total of 458 mosquito collections occurred over 10 individual weeks of sampling. For

276   assessments of spatial and temporal signals, 41 houses (65%) with 205 mosquito sampling events

277   met the criteria for inclusion. For assessments of household characteristics, 43 houses (68%)

278   with 189 mosquito sampling events met the criteria for inclusion. For SES models, 32 houses

279   (51%) with 160 mosquito sampling events met the criteria for inclusion.

280

281   *Climate*

282   Weekly *Ae. aegypti* female presence was significantly correlated with precipitation, with the

283   strongest correlation at 1-week lag (r= 0.76, p = 0.001), and another significant lag at 3 weeks

284   (r=0.66, p=0.036). Weekly *Ae. aegypti* female presence was also significantly correlated with

13

285   mean (r=0.75, p=0.012) and maximum (r=0.84, p=0.002) temperature, in the same week.

286   Minimum temperatures were not significantly correlated with *Ae. aegypti* presence at any lag.

287   A multi-model selection on a beta regression of the proportion of households with female

288   *Ae. aegypti* presence as a function of mean temperature, maximum temperature, and precipitation

289   for the week, and precipitation lagged 3 weeks, yielded two models within 2 AICc of the top

290   model, and an averaged model of *Ae. aegypti* presence as a function of mean temperature, and

291   precipitation lagged 1 week, had a pseudo R^2 of 0.71. The current week's temperature was

292   significant ($\beta = 0.63$, SE=0.29, p=0.03) in the overall model, while precipitation of the prior

293   week was not ($\beta = 0.74$, SE= 1.94, p=0.051).
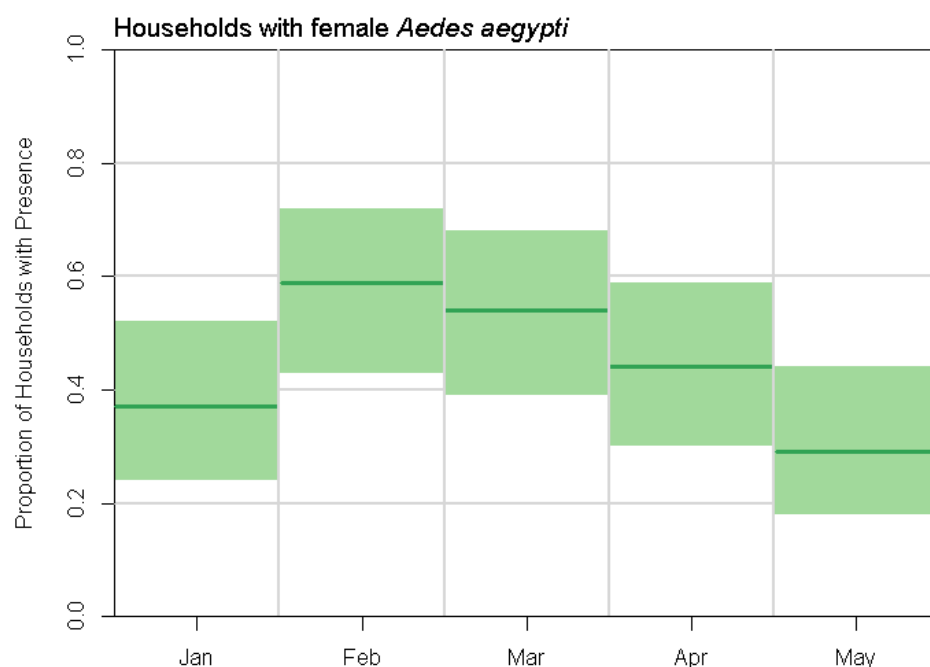
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295
296   **Fig 3. Female *Aedes aegypti* presence in households in Huaquillas, Ecuador, by month in**
297   **2017.** Month proportions and 95% confidence intervals for 41 households used in this dataset.
298   Chi-squared test for difference in proportions: 9.56, p=0.0484).
299
300   *Temporal and spatial patterns of Ae. aegypti presence*

14

301   The proportion of positive households was highest in February and lowest in May (Fig 3). In

302   January, the proportion of positive households was 0.38; this increased to 0.59 in February

303   before steadily declining. The monthly differences were significant (χ^2=9.564, p=0.048), but a

304   post hoc Fisher's exact test did not identify specific month-to-month differences (S1 Table).

305   The positive proportion of houses by cluster varied from 0.15 to 0.70 (S2 Table). There

306   were significant differences between clusters (χ^2=32.185, p=0.0002). A post hoc Fisher's exact

307   test identified significant pairwise differences between four cluster pairs (Fig 4 and S3 Table).

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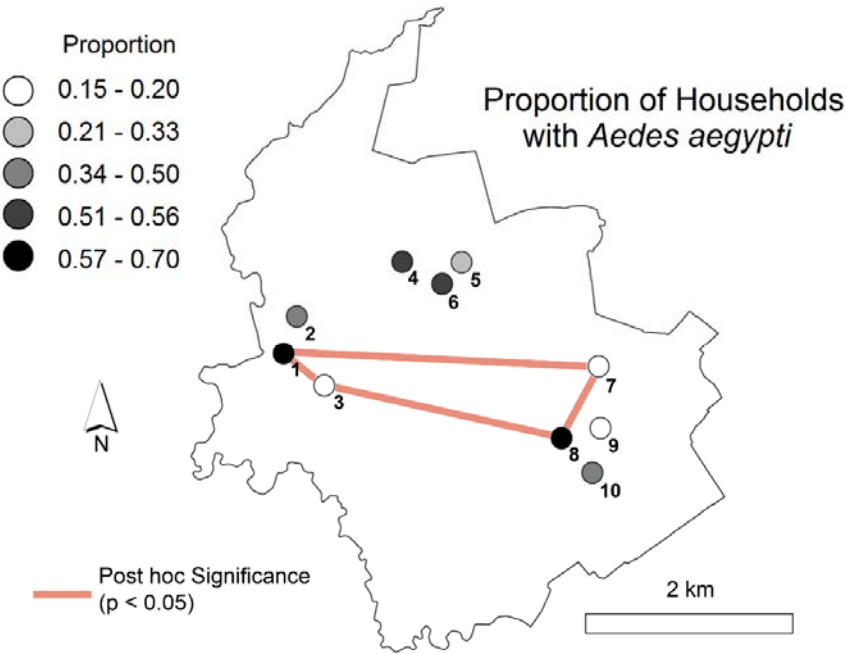322   **Fig 4. Proportion of households with female *Aedes aegypti* by cluster**. The proportion of
323   sampling events with female *Aedes aegypti* mosquitoes during January-May is indicated by
324   shading (grey). Orange lines connecting clusters indicate a statistically significant difference in
325   *Aedes aegypti* presence (post-hoc Fisher's exact test).

326

327   **Bivariate tests for SES factors**

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328   All respondents considered dengue fever to be a severe disease and correctly answered

329   questions about the transmission cycle of the disease, so these variables were not included in this

330   analysis. Among demographic variables, the number of people living in a household, the number

331   of years a head of household (HOH) had lived in the neighborhood, and female HOHs were

332   significantly associated with household presence of female *Ae. aegypti* (Table 1). Factors

333   describing the physical conditions of households were not found to be significant predictors of

334   *Ae. aegypti* presence. However, three of the four variables describing infrastructure and public

335   services were significant. Experiencing frequent interruptions in piped water service and

336   biweekly trash collection were positively associated with presence, while use of a septic tank

337   was negatively associated. Of mosquito prevention methods surveyed, only reported use of

338   Abate® larvicide, was significant, with a positive effect. Employment and travel habits were not

339   found to be significant.

340

Table 1. Household level social-ecological factors associated with female *Aedes aegypti* presence (AA) in homes in Huaquillas, Ecuador. Variables given as average value or proportion. Significant associations (p<0.05) are in bold. The t statistic is given when the t test is used and an odds ratio (OR) is given when Fisher's exact test is used.

	AA	All households	t-statistic/ OR	p value	test
Demographics					
People Living in the House	4.862	4.545	2.27	0.02	
Years Living in Neighborhood	24.460	22.111	2.60	0.01	t
Age of HOH	49.115	47.608	1.35	0.18	
Female HOH	0.299	0.222	2.28	0.02	
HOH Beyond Primary Education	0.460	0.455	1.04	1.00	Fisher
HOH Makes Basic Income	0.356	0.291	1.79	0.08	
Physical Condition					
Number of Rooms	2.747	2.651	1.27	0.21	t
Good Overall Condition	0.460	0.481	0.85	0.66	
Good Flooring	0.517	0.450	1.66	0.11	
Screens on Windows	0.230	0.222	1.09	0.86	
Shaded Patio	0.816	0.836	0.77	0.56	Fisher
Abandoned Houses Nearby	0.655	0.704	0.65	0.20	
Unpaved Road	0.563	0.614	0.68	0.23	
Infrastructure and Services					
Stores Water	0.805	0.741	1.88	0.07	
Reliable Piped Water	0.632	0.725	0.42	0.01	Fisher
Uses Septic Tank	0.057	0.116	0.31	0.02	
Biweekly Trash Collection	0.701	0.598	2.25	0.01	
Occupation					
Outdoor Labor	0.425	0.439	0.90	0.77	Fisher
Indoor Service	0.460	0.481	0.85	0.66	
Prevention					
Treated Water in Past 30 days	0.356	0.307	1.53	0.21	
Uses Abate® Larvicide	0.862	0.921	0.19	0.01	Fisher
Drains Standing water	0.954	0.947	1.30	0.76	
Closes Windows and Doors	0.966	0.947	2.06	0.35	
Other					
HOH Works Outside of the City	0.218	0.206	1.14	0.72	
Does Not Leave Neighborhood for Work	0.966	0.942	2.37	0.23	Fisher
HOH=head of household					

341

342 *Social-ecological models of household female Aedes aegypti presence*

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343   There were eight models within 2 AICc of the top ranked model. All eight models contained the

344   variables: number of years the HOH has lived in the neighborhood (increased exposure), and

345   reliable (un-interrupted) water supply (protective). Additional variables appearing in one of more

346   models, in order of importance (weight) were use of a septic tank, female HOH, the number of

347   people in the household, and biweekly trash collection. Interestingly, the use of larvicide was not

348   found to be important in the top models. The model averaged parameter estimates are given in

349   Table 2, in which odds ratios (OR) denote risk of exposure for OR>1, and protective exposure

350   for OR<1. Relative variable importance among these models is in Table 3. We see that the two

351   most important variables are also the two statistically significant model parameters overall:

352   number of years the HOH has lived in the neighborhood, and reliable water supply.

Table 2. SES factors and female *Aedes aegypti* presence in households in Huaquillas, Ecuador. Weighted best-fit model averaged parameter estimates, standard error (SE), odds ratio (OR) and 95% confidence intervals on the ORs included for fixed effects. Bold indicates the variable is statistically significant at $\alpha > 0.05$. Random effects of cluster and month are given as variance measures, and were included in every model.

Fixed Effects					
	Estimate	SE	Pr(>|z|)	OR	95% CI
(Intercept)	- 0.19	0.34	0.58	0.82	0.23 - 6.28
Years Living in Neighborhood	0.04	0.02	0.03	1.04	1.00 - 1.08
Reliable Piped Water	-0.99	0.46	0.03	0.37	0.15 – 0.93
Uses Septic Tank	-0.61	0.99	0.54	0.54	0.03 - 1.63
People Living in the House	0.05	0.09	0.60	1.05	0.93 - 1.44
HOH Female	0.11	0.32	0.73	1.12	0.60 - 4.82
Biweekly Trash Collection	0.11	0.34	0.75	1.12	0.58 – 5.90

Random Effects		
Groups	Variance	Std. Dev
Cluster	0.60	0.78
Month	0.19	0.44

353

354

Table 3. Relative importance of each variable included in models. Calculated as a sum of the Akaike weights over all the models in which the variable appears. The number of top models which include the variable is also included.

	Summed Akaike Weights	# of Models Containing
Years Living in Neighborhood	1.00	8
Reliable Water Supply	1.00	8
Uses Septic Tank	0.40	3
People Living in the House	0.34	3
Female HOH	0.20	2
Biweekly Trash Collection	0.18	2

355

Discussion

357 In this study we investigated the drivers of household-level female *Ae. aegypti* presence

358 in Huaquillas, Ecuador, to identify social-ecological conditions that promote potential arboviral

359 disease risk to inform vector control and intervention strategies. Precipitation during the study

360 period was anomalously low compared to long-term averages (Fig 1). In several recent studies,

361 the role of drought in altering the way water storage occurs in urban landscapes has been

362 highlighted as a potential key factor in *Ae. aegypti* habitat in urban environments [54–60]. Given

363 this was a particularly dry year, in an already arid environment, the role of precipitation in the

364 timing of *Ae. aegypti* presence may be different than in an average year. We found that the prior

365 week's precipitation was an important predictor of *Ae aegypti* presence, in combination with the

366 current week's temperature. Whether the role of precipitation is emphasized or diminished in a

367 dry year is likely mediated by human-driven water storage and use on the landscape. In outdoor,

368 rain-filled habitats, accumulated precipitation can generate oviposition sites for *Ae. aegypti*, but

369 extreme precipitation events can flush out those same larval habitats [61,62]. Thus, the

370 relationship between precipitation and vector population size is not linear, and may depend more

19

371   on the intensity of precipitation events [9,63]. In our study, *Ae. aegypti* presence was

372   significantly correlated with precipitation lagged by 3 weeks, and 1 week, alone, but when

373   included in a model with temperature, the longer lag dropped out of model importance, and the

374   1-week lag was found not to be significant, suggesting a stronger role of temperature in this

375   location. In rain-filled habitats, precipitation events increase the suitability of larval habitats,

376   prompting eggs of *Ae. aegypti* to hatch and begin development [64]. The 1-week lag in

377   precipitation likely indicates sufficient humidity and moisture for mosquito activity in the current

378   week, and perhaps trigger egg hatching, but is likely too short a time-frame for development to

379   flying adults. The 3-week lag identified in this study is longer than the typical development time

380   for *Ae. aegypti* [65], however in an arid environment such as this, larval habitat may dry after

381   precipitation events, increasing the time necessary to develop [66,67]. In the urban environment,

382   the timing and degree to which precipitation influences vectors is also highly modulated by the

383   social-ecological environment [11,68]. The role of precipitation may be more identifiable when

384   containers and buckets are visibly on household premises, but is diminished when alternative

385   oviposition sites such as water storage tanks, cisterns, and other water infrastructure sites are

386   available [54,69].

387   During the study period, mean temperatures in Huaquillas were within historical ranges

388   (Fig 1). Laboratory studies of *Ae. aegypti* have found nonlinear relationships between mean

389   temperature and physiological traits [70,71]. The weekly mean temperatures assessed in our

390   climate analysis range from approximately 26 and 28°C. Biting, development, fecundity, and

391   mortality are positively correlated with mean temperatures within this range [72]. We found that

392   weekly *Ae aegypti* presence was significantly associated with mean temperatures of the same

393   week. This captures the immediate effect of temperature on biting by *Ae. aegypti* in households

394   where people reside [73]. Outdoor temperatures higher than 21°C may drive *Ae. aegypti* indoors

395   to reduce mortality [74], and indoor resting behavior is characteristic of *Ae. aegypti*, especially

396   while processing blood meals [75], so sheltering in shade indoors may be an adaptive strategy for

397   cooling. Prior studies of *Ae. aegypti* in desert climates have occurred in Texas, Arizona, and

398   parts of Mexico [76,77]. In Mexico, a study found differences in the age structure of *Ae. aegypti*

399   populations between two cities in desert and steppe climates, with older *Ae. aegypti* populations

400   in the desert [76]. While precipitation did not differ a lot between the two sites, the cooler steppe

401   population underwent a period of low humidity, which may impact survival. This is important

402   for disease transmission, as *Ae. aegypti* must live long enough to feed and become infectious,

403   and the authors suggested that the higher population turnover in the steppe may contribute to the

404   surprising lack of dengue establishment. This points to the complexities of interactions between

405   temperature (which can exceed optima for survival), precipitation, and sufficient humidity in an

406   arid environment.

407   In this study, the presence of *Ae aegypti* at the household level differed across months.

408   Changes in *Ae. aegypti* presence at coarse temporal scales are driven by climatic factors [78,79],

409   and increased household *Ae. aegypti* presence in Huaquillas during the study period can be

410   attributed to differences in precipitation and temperature. The seasonal nature of Huaquillas'

411   climate may thus point to time periods when targeted vector control interventions would be

412   optimally effective.

413   The household clusters in this study served as a neighborhood-scale measure of space.

414   Presence of *Ae. aegypti* varied significantly between the clusters, meaning there is a high degree

415   of sub-city level spatial variability. Unfortunately, at this sample size, more detailed spatial

416   trends are hard to identify, but point to the need for future studies into heterogeneity at sub-city

417   scale. *Ae. aegypti* has a short dispersal range of about 250 m [35], and its dispersal can be limited

418   by barriers such as major roads or stretches of land unsuitable for oviposition [80]. Several

419   studies have identified distinct vector subpopulations existing in close proximity in urban

420   settings [81–83]. The implications of this in a busy border city call for further studies in this

421   location.

422

423   **Social-ecological drivers of risk**

424   In single variable models of *Ae aegypti* presence, the number of years the HOH lived in

425   the neighborhood, the number of people living in the household, and whether the HOH was

426   female were all important and significant demographic components of the social-ecological

427   system. Infrastructurally, reliable piped water supply and trash collection were important and

428   significant, as was whether the household was on a septic tank system, and if the household used

429   Abate® larvicide. Households with *Ae. aegypti* were significantly more likely to use larvicide,

430   which suggests that household members are sensitive to *Ae. aegypti* presence, and may increase

431   preventative actions when the mosquito is detected. This may also mean that control efforts by

432   the Ministry of Health are well targeted at households with *Ae. aegypti*, but may require

433   increased capacity and frequency.

434   In single variable models, septic tanks were found to be protective against mosquito

435   presence, even though septic tanks act as persistent oviposition sites in other locations [84–86].

436   In the best-fit model, the role of septic tanks was not significant, so the direction of exposure

437   association (protective or risky) was not clear. Septic tanks in Huaquillas are typically

438   underground with no suitable entrance for mosquitoes (Fig 4), and are used widely in the

439   periphery of the city where sewer infrastructure has only recently become available. All

22

440   households with septic tanks were in cluster 7 which is in a low-density residential area on the

441   city outskirts. Given that septic tanks occur in peripheral areas where municipal water and sewer

442   infrastructure is a recent addition, and appeared to confer a protective association, this

443   relationship warrants further examination.

444   While septic tanks, along with female HOH, the number of people living in the

445   household, and trash collection were all important to the best fit model to the social-ecological

446   system model, the two significant variables, the number of years the HOH lived in the

447   neighborhood, and reliability of water supply were the most important and significant social-

448   ecological variables associated with risk of *Ae aegypti* presence at the household level.

449   Interestingly, there was an increase in exposure risk with the number of years HOH lived in the

450   neighborhood, and a protective effect of having reliable water supply. The role of water

451   infrastructure in exposure risk to *Ae aegypti* at the household level has been found in previous

452   studies, and points to the fundamental and vital role reliable water supply and urban

453   infrastructure play in *Ae aegypti* endemic environments. Given the importance of septic tank

454   usage, and the clear role of water supply, this study suggests that urban infrastructure around

455   water supply and use is playing a large role in the risk of *Ae aegypti* presence in the household in

456   Huaquillas.

457

458 **Fig 4.** Example of a septic system in Huaquillas, August 2019. Septic systems are commonly
459 used by households not connected to the municipal sewer network. A vent pipe connected to the
460 underground tank rises through a sealed opening in the access cover. The vent pipe stands about
461 3 meters high. (Photo Credit: R. Sippy)
462

463

464 **Conclusion**

465 In this study we explored climatic and social-ecological factors associated with household-level

466 female *Ae. aegypti* presence, and temporal and spatial trends across an arid border city in

467 Ecuador. The results of our analyses may inform potential control strategies (timing) and

468 interventions (improved water infrastructure) to reduce vector-borne disease risk in the city of

469 Huaquillas in southern coastal Ecuador. Given that this study was conducted in an exceptionally

470 dry year and the evidence for water supply and usage as major factors in household-level risk,

471 water-related interventions at multiple scales could be important.

472   The social-ecological environment that influences the urban *Ae. aegypti* mosquito varies

473   substantially from place to place. Local studies are especially needed to guide policy and inform

474   interventions. Integrated vector control requires information collection, assessment, and decision

475   making at local scales. While there is value in national to global studies of *Ae. aegypti*

476   populations, these studies produce information that is of most relevance for national or

477   international decision-makers. We acknowledge that there are logistical and resource related

478   challenges inherent in conducting investigations at smaller scales, and in this study, while

479   leveraging an immensely rich dataset over several months, we still ran into issues of small

480   sample size. However, in order to integrate social-ecological systems approaches into essential

481   local-scale work, we suggest that the design and methodological approach of this study is one

482   example of how some of these challenges can be met. As many parts of the world become

483   increasingly urban and ever more connected to global transportation networks, the number of

484   places with endemic *Ae. aegypti* populations will increase. Climate change throughout the 21st

485   century is also set to increase the area suitable for *Ae. aegypti* presence [87]. These developments

486   will further increase the importance of research at multiple scales to guide management and

487   policy. Vector control will continue to be a critical component of arboviral disease prevention,

488   even as additional intervention options become available. Understanding the systems which

489   allow vectors to exist, persist, and transmit disease will remain critical in promoting human

490   health and wellbeing for the foreseeable future.

491

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499

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757

758 **Supporting information**

759 **S1 Table. Matrix of *p* values from post hoc tests on pairs of months.**
760

Month	January	February	March	April	May
January					
February	0.254				
March	0.449	0.824			
April	0.725	0.449	0.725		
May	0.725	0.139	0.215	0.449	

761 Fisher's exact test was conducted using the proportion of sampled households where *Aedes*
762 *aegypti* was present. P values adjusted using the false discovery rate method [49].
763
764 **S2 Table. Proportion of households found present for *Aedes aegypti* by cluster**.
765

Cluster	Presence	Lower CI	Upper CI	n
1	0.70	0.48	0.85	20
2	0.50	0.24	0.76	10
3	0.20	0.09	0.39	25
4	0.56	0.37	0.73	25
5	0.33	0.19	0.51	30
6	0.53	0.30	0.75	15
7	0.15	0.05	0.36	20
8	0.70	0.52	0.83	30
9	0.20	0.06	0.51	10
10	0.45	0.26	0.66	20
χ^2	32.185	p	**0.000185**	

766 Table includes confidence intervals of 95% and the results from a chi square test.
767 **S3 Table. Matrix of p values from post hoc tests on pairs of clusters.**
768

Cluster	1	2	3	4	5	6	7	8	9	10
1										
2	0.617									
3	**0.012**	0.258								
4	0.578	1.000	0.090							
5	0.090	0.642	0.578	0.258						
6	0.656	1.000	0.154	1.000	0.426					
7	**0.012**	0.247	0.870	0.056	0.426	0.111				
8	1.000	0.500	**0.008**	0.599	0.060	0.573	**0.007**			
9	0.090	0.578	1.000	0.246	0.866	0.426	1.000	0.060		
10	0.426	1.000	0.258	0.713	0.713	0.874	0.247	0.250	0.462	

769 Fisher's exact test was conducted using the proportion of sampled households where *Aedes*
770 *aegypti* was present. P values adjusted using the false discovery rate method [49].
771