Received: 5 October 2020 | Accepted: 7 June 2021

DOI: 10.1111/1365-2664.13951

RESEARCH ARTICLE

Journal of Applied Ecology | BRITISH ECOLOGICAL SOCIETY

Variable coverage in an Autocidal Gravid Ovitrap intervention impacts efficacy of *Aedes aegypti* control

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Funding information
NIH Clinical Center, Grant/Award Number: R21AI128953; National Center for Emerging and Zoonotic Infectious Diseases, Grant/Award Number: U01CK000512

Handling Editor: Andrew Park

Abstract

1. Control of the arboviral disease vector *Aedes aegypti* has shown variable levels of efficacy around the globe. We evaluated an Autocidal Gravid Ovitrap (AGO) intervention as a stand-alone control tool for population suppression of *A. aegypti* in US communities bordering Mexico.
2. We conducted a cluster randomized crossover trial with weekly mosquito surveillance of sentinel households from July 2017 to December 2018. The intervention took place from August to December of both years. Multilevel models (generalized linear and additive mixed models) were used to analyse the changes in population abundance of female *A. aegypti*.
3. We observed that female populations were being suppressed 77% (2018) and four times lower outdoor female abundance when AGO coverage (number of intervention AGO traps that surrounded a sentinel home) was high (2.7 AGOs/house). However, we also observed that areas with low intervention AGO coverage resulted in no difference (2017) or slightly higher abundance compared to the control. These results suggest that coverage rate might play a critical role on how populations of female *A. aegypti* are being modulated in the field. The lack of larval source habitat reduction and the short duration of the intervention period might have limited the *A. aegypti* population suppression observed in this study.
4. *Synthesis and applications*. The mosquito, *A. aegypti*, is a public health concern in most tropical and subtropical regions. With the rise of insecticide resistance, the evaluation of non-chemical tools has become pivotal in the fight against arboviral disease transmission. Our study shows that the AGO intervention, as a stand-alone control tool, is limited by its coverage in human settlements. Vector control programmes should consider, that if the target coverage rate is not achieved, measures will be ineffective unless coupled with other control approaches. Although our multilevel modelling was focused on *A. aegypti* and the AGO, the approach can be applied to other mosquito vector species.

KEYWORDS
Aedes aegypti, AGO, dengue fever, mosquito traps, multilevel modelling, population suppression, vector control

1 | INTRODUCTION

Aedes aegypti (L.) is established in most of the tropical and subtropical regions of the world (Kamal et al., 2018). Its adaptation to man-made environments has made it a public health threat for urban transmission of dengue, chikungunya, Zika and yellow fever viruses (Eder et al., 2018; WHO, 2017a). Controlling *A. aegypti* has traditionally relied on the use of insecticide-based (e.g. larvicides, ultra-low volume spraying, fogging and treated screens) and non-insecticide-based approaches (e.g. elimination of breeding sites and physical barriers; Achee et al., 2015; WHO, 2017a). These methods have resulted in variable levels of efficacy in reducing *A. aegypti* populations (Bowman et al., 2016; Esu et al., 2010) and pathogen transmission reduction (Sharp et al., 2019). However, some of these methods might be operationally difficult, labour intensive to execute or not practical in areas with an established vector population (WHO, 2016). With increasing reports of insecticide resistance (Deming et al., 2016) and elimination of aquatic habitats unfeasible on a city-wide scale, the evaluation of alternative surveillance and control methods is needed to reduce the burden of human-amplified arboviruses.

The surveillance and control of insect vectors has always relied on tools that can exploit the general biology of its target (Dent & Binks, 2020). For mosquitoes it has been observed that gravid females use visual, humidity and olfactory cues to locate suitable oviposition sites (McCall & Cameron, 1995), with chemical cues playing a key role during site selection (Navarro-Silva et al., 2009). Ovitraps are artificial containers that retain water and exploit the oviposition seeking behaviour of female mosquitoes by simulating larval habitats (Silver, 2013). They can be used for mosquito research and the attraction is often enhanced by natural or artificial attractants (e.g. hay) which lure ovipositing females into these water containers. While initially used for surveillance and ecological studies (Chaves & Friberg, 2021), ovitraps can also be used for mosquito removal which when scaled-up, have the ability to achieve population-level control (Barrera et al., 2014). In 2013, the use of an improved Autocidal Gravid Ovitrap (AGO) was proposed for the surveillance and control of *A. aegypti* by trapping ovipositing females (Mackay et al., 2013).

The AGO has been shown as an efficient surveillance and control tool in Puerto Rico and has reduced chikungunya virus incidence in humans (Sharp et al., 2019). Before wide implementation of this tool by vector control programmes in other regions, its evaluation based on community acceptance, field operational performance and overall efficiency for both surveillance and control, needs to be assessed under different local settings (Garcia-Luna et al., 2019; Gunning et al., 2018; Lenhart et al., 2020). The AGO has been shown to be a cost-effective tool for the surveillance of adult *A. aegypti* in both San Antonio (Obregón et al., 2019) and the Lower Rio Grande Valley (LRGV) region (Martin et al., 2019) in South Texas. However, the operational effectiveness as an intervention tool has not been evaluated in much of the continental United States, including Texas. The current study evaluates a cluster randomized crossover (CRXO) trial of an AGO intervention in South Texas to reduce female *A. aegypti* populations.

2 | MATERIALS AND METHODS

2.1 | Ethic statement

This project received approval from the Institutional Review Board of Texas A&M University (IRB2016-0494D). We obtained individual written consent from each household owner for the weekly indoor and outdoor entomological surveillance.

2.2 | Study area

The study was conducted in Hidalgo and Cameron counties, Texas, US. These counties are part of the region known as the LRGV located along the US–Mexico border (see Appendix S1 Figure S1). These counties belong to one of the few areas in the continental US where local vector borne disease transmission of dengue, chikungunya and Zika viruses has occurred. From 2017 to 2020 there have been a total of 15 documented locally acquired cases of dengue and five cases of Zika (CDC, 2021). Across the border in the state of Tamaulipas, Mexico, more intense transmission and higher disease burden of dengue and Zika have been recorded (Olson et al., 2020; Thomas et al., 2016). The weather within this region is considered humid subtropical, with a cold/dry season from November to February (7–21°C), and a rainy season that starts in April (18–30°C), peaks in September (23–33°C) and finishes in October (19–31°C; NOAA, 2017). Climatic data were obtained from McAllen airport, which is close to all studied communities (average distance of 33.5 km, $SD = 11.2$). We assume that its weather records are a suitable proxy of regional weather patterns in the study area.

2.3 | Community selection and sample size

The 2010 census block groups were separated in two socioeconomic groups: low income ($15,000–$29,999) and middle income ($30,000–$40,000), based on mean household income. Census blocks within a 30 km radius from our operation base were used to identify candidate communities (group of census blocks with the same name) using 2016 satellite imagery in Google Earth (California, USA). These candidate communities were selected based on size (range of 20 to 85 households), level of isolation (≤1 adjacent residential or urban landscape that was not found crossing a two-way road) and safety for field personnel.

From September 2016 to June 2017, we evaluated 13 communities for mosquito sampling using one indoor and outdoor AGO (see Appendix S1 Figure S2; Juarez, Garcia-Luna, et al., 2021). In this study we refer to the AGOs used for weekly surveillance as Sentinel AGO or SAGO, and those deployed during the intervention as Intervention AGO or IAGO (BioCare, SpringStar Inc). Both the SAGO and IAGO are the same trap, just deployed in different ways. After starting to sample baseline mosquito abundance, five communities had to be removed due to low community member participation, and for security reasons. In July 2017 (week 30), the remaining eight communities had surveillance efforts increased to an average of one SAGO per 100 m^2 (with the exception of La Vista and Cameron with 1 trap per 120 m^2). This coverage resulted in five to seven SAGOs per community. These communities were randomly assigned into two groups (GR1 and GR2), with two low- and two middle-income communities per group (see Appendix S1 Table S1).

Household recruitment and selection for the weekly SAGO surveillance has been detailed elsewhere (Martin et al., 2019). Briefly, random households within each community were visited until the desired coverage was achieved. The percentage of households surveyed varied due to the absence of community members granting access to their households during weekly visits throughout the study period. If a household dropped out of the study, we tried to recruit its neighbour to the right until a new household was recruited. A total of nine surveillance houses, seven from middle-income and two from low-income communities, had to be replaced from July 2017 to August 2018. We were unable to replace the two houses from low-income communities, since all available homeowners within these communities did not grant consent for placing the indoor trap. All middle-income households were replaced.

2.4 | Sentinel AGO (SAGO) entomological surveillance

Indoor and outdoor adult mosquito surveillance was done on a weekly basis from 23 July 2017 (week 30) to 12 December 2018 (week 50). In this study we adjusted the SAGO attractant as explained by Martin et al. (2019). Briefly, we reduced the amount of hay (from 30 to 3 g) and water (from 10 to 3.5 L) due to multiple complaints from community members about the odour of both the indoor and outdoor traps, while sustaining the 10% recommended dose of hay to water (Barrera et al., 2014; Reiter et al., 1991). SAGOs were surveyed from Monday to Wednesday. If a homeowner was absent, but access to the outdoor SAGO was feasible only the outdoor trap was surveyed on that day, all pending houses had a second visit scheduled on Thursday or Friday of the same week. We were unable to conduct surveillance in the community of Chapa in July 2018, due to a flooding event. In June 2018 mosquito control efforts (adulticide by ultra-low volume spraying and larvicide with Bti briquette in canals) by the county of Hidalgo were deployed in the communities of Chapa and Cameron as a response to a flooding event.

Collected mosquitoes were identified on the glue board (Catchmaster), removed with a teasing needle and separated by species (*A. aegypti*, *A. albopictus*, *Culex* spp. and other spp.), sex (male and female) and female condition (unfed, gravid and blood fed). Traps were serviced on every visit by replacing the hay infusion (~3.5 L of water and 3 g of hay) each week, while glue boards were replaced as needed; usually every 2 months (Barrera et al., 2014).

2.5 | Intervention AGO (IAGO) deployment

The intervention followed the procedure carried out in Puerto Rico (Barrera et al., 2014), without the concurrent larval source habitat reduction campaign in the communities prior to the deployment of IAGOs (Figure 1). We used a CRXO design (Arnup et al., 2017). Briefly, a CRXO trial is an evaluation in which clusters are placed into the intervention or control treatments for a period of time before they are switched to the other treatment. Allowing a washout period between the switch to prevent carry-over effects from the intervention. This type of study design can be used to evaluate interventions that have temporal effects and allows smaller sample sizes (WHO, 2017b) while also allowing all communities in the study to receive the intervention treatment for 1 year. Accordingly, Group 1 (GR1) was randomly selected to be the intervention community for 2017 and Group 2 (GR2) the reference; in 2018 the communities were switched allowing for a 9-month washout period.

Records were kept for which houses were occupied and/or unoccupied. The intervention recruitment targeted 80% of the households in a community receiving three IAGOs per home (Barrera et al., 2014). We visited each household at least three times in the 2 weeks prior to trap deployment. Houses that had previously dropped out from the SAGO surveillance were offered to participate in the intervention. Community members were allowed to enrol in the project up until the trap reset of October for each year.

One IAGO was placed in the front, side and back of the house, prioritizing shaded areas when available. Community members that requested two IAGOs in their homes (Rio Rico = 2, La Vista = 10, La Bonita = 1) were still included in the study. IAGOs were deployed in August during week 33, reset in October during week 41 and removed in December during week 50 for both 2017 and 2018. The hay infusion varied due to the 2-month period of deployment (10 L of water and 3 g of hay), where a 4% dose of hay to water was used. During the reset we replaced glue boards, hay infusion and IAGOs that were damaged or lost. Records were kept for each IAGO regarding total mosquito (Culicidae) counts, placement area (front, side or back), the presence of mosquitoes inside the IAGO (larvae, pupae and/or adults) and the condition of each IAGO regarding water, the glue board and if the IAGO was lost, removed or damaged. When assessing the glue boards after 2 months, we were only able to count the total number of Culicidae specimens as we were not confident

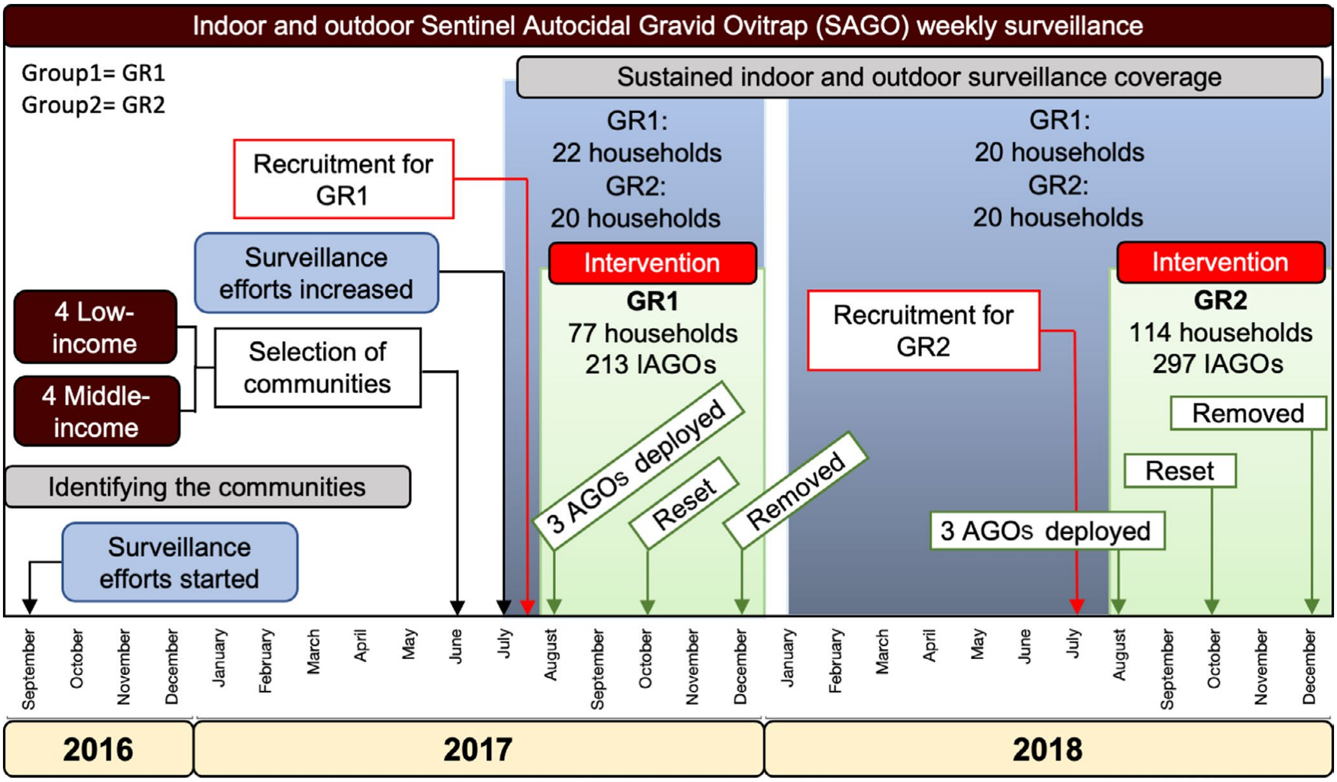

FIGURE 1 Timeline of the Autocidal Gravid Ovitrap (AGO) trial conducted in South Texas, USA. Households with sustained indoor and outdoor SAGO surveillance did not have three intervention AGOs (IAGOs) deployed outside during the intervention

enough to judge genus or species given the degradation of many specimens.

2.6 | Statistical analysis

We evaluated the weekly SAGO indoor and outdoor *A. aegypti* female abundance using generalized linear mixed models (GLMMs) and generalized additive mixed models (GAMMs) for count data. These models were chosen given their ability to account for unbalanced, or variable sampling efforts, in our dataset. We employed mixed models for the potential lack of spatial (random effect for households nested within communities) and temporal independence (random effect for sampling week) in our data (Chaves, 2010). Initially, we assumed that mosquito counts followed a Poisson distribution (variance = mean) and then compared the fits with those of overdispersed counts (variance > mean; Sileshi, 2006; White & Bennetts, 1996). The quasi-Poisson and negative binomial (NB) distributions were used to evaluate if variance increased linearly or quadratically with the mean (referred as NB type 1 and type 2 in the R packages used, to avoid confusion with the R code hereinafter referred as such; Hardin & Hilbe, 2007). All models were generated with R 3.6.1 (R Core Team) using the GLMMTMB and GAMM4 packages (Magnusson et al., 2020; Wood & Scheipl, 2020).

We used the GLMM approach to evaluate the AGO intervention considering two distinct scenarios:

TABLE 1 Generalized linear mixed models and generalized additive mixed model, fixed and random effect structure with assumptions, Akaike information criterion (AIC) correspond to the best fit model (NB type 2)

Type	Offset	Fixed
GLMM: imm. effect	log (days of trapping)	Socioeconomic status * Trap placement + Year * Intervention Phase + Precipitation + Temperature
GLMM: short effect – reduced time	log (days of trapping)	Socioeconomic status * Trap placement + Year * Intervention Phase + Precipitation + Temperature + Week or Month
GLMM: short effect – delayed impact	log (days of trapping)	Socioeconomic status * Trap placement + Year * Intervention Phase + Precipitation + Temperature
GAMM: coverage	log (days of trapping)	Socioeconomic status * Trap placement + Year

*Indicates an interaction between effects and | indicates a nested (or conditional) random factor; log indicates natural logarithm.

1. The intervention effects were immediate after the IAGOs were deployed and lasted the whole intervention period—immediate effect models.
2. The intervention effects were transient and did not last for the whole intervention period—short effect models.

In Table 1 we show the fixed and random effects structure for these two approaches. For a detailed step by step procedure see Appendix S2 Supplementary Methods: Statistical analysis, which includes further explanation about model selection. Briefly, the full GLMM model of each scenario included two interaction terms: socioeconomic status (low or middle income) by placement of the SAGO (indoor or outdoor), and year (2017 or 2018) by treatment phase (pre-intervention, control or intervention), with covariates for precipitation and average temperature. In addition to these effects, the short effect models evaluated if the intervention impact was short lived with covariates for week or month (reduced time), or if the intervention impact was observed 1 or 2 weeks after deployment (adjusting the pre-intervention phase for a longer period to reflect these delays; delayed impact; see Dataset S1).

We used a GAMM approach to evaluate if time (week) and IAGOs deployed (IAGO coverage or density) in an area had a nonlinear relationship with female *A. aegypti* abundance. To model the effect of IAGO coverage, we generated a new variable termed Coverage Rate (CovRate = total no. of IAGOs/total no. of houses in a 200 m radius, based on the mean distance travelled for *A. aegypti* females in the region, Juarez et al., 2020) which accounts for size of a community, weighting the effect based on the number of neighbouring houses from the SAGO traps. Since large communities might have a higher count of IAGOs deployed but a low coverage based on the number of houses that participated in the intervention. We used spline penalizing effects on the covariates of week and CovRate to allow the relationship of female *A. aegypti* vary nonlinearly (Wood, 2017).

Data heteroscedasticity was evaluated by plotting the residuals as function of predicted values for the distribution models. The full GLMM models were simplified using backward elimination (Faraway, 2015), where parameters accounting for the two-way interaction and single parameters were removed based on the significance of the fixed effects estimates at an $\alpha = 0.05$. We also carried out an information-theoretic approach to select among non-nested models with the same number of parameters and compared these results with the best fit models from the backward elimination procedure (see Appendix S2 Table S18; Burnham & Anderson, 2002; Whittingham et al., 2006). Models were selected based on the lowest Akaike information criterion (AIC), a metric for model selection that balances goodness-of-fit and the number of parameters (Burnham & Anderson, 2004).

3 | RESULTS

3.1 | Indoor and outdoor SAGO surveillance

To evaluate the AGO trap as an intervention tool we analysed the SAGO weekly results obtained only from the surveillance activities between July (week 30) of 2017 and December (week 50) of 2018. In Figures 2 and 3 we present the indoor and outdoor SAGO results of female *A. aegypti* respectively. During the surveillance period we were able to collect a total of 2,929 females in 2017 and 4,117 in 2018. For low-income communities during the intervention period, we collected a total of 213 indoor female *A. aegypti* in GR1 (Figure 2a) and 50 in GR2 (Figure 2b). In middle-income communities during the same period, we collected 72 indoor female *A. aegypti* in GR1 (Figure 2c) and 53 in GR2 (Figure 2d). For low-income communities during the intervention period, we collected a total of 1,523 outdoor female *A. aegypti* in GR1 (Figure 3a) and 933 in GR2 (Figure 3b). In middle-income communities during the same period, we collected 856 outdoor female *A. aegypti* in GR1 (Figure 3c) and 483 in GR2 (Figure 3d).

3.2 | Community participation

During the intervention period of 2017 we had a community participation of 52% (53/102 houses) in low- and 56% (24/43 houses) in middle-income communities (Table 2). A total of 213 IAGOs were deployed, 139 in low-income communities with an average of 44.5 (*SD* = 6.6) Culicidae/IAGO/2 months, and 74 in middle-income communities with an average of 25.1 (*SD* = 2.9) Culicidae/AGO/2 months. Each of the deployed IAGO was assessed two times (October reset

Smoothed	Random	Assumption	AIC
	Week + Community (House)	Intervention effect was immediate and lasted during the whole intervention period	9,744.8
	Community | House	Intervention effect was short lived after the deployment and reset of the AGOs	1 week: 9,938.4 4 weeks (1 month): 9,947.9
	Week + Community | House	Intervention effect was observed 1 or 2 weeks after deployment and reset of the AGOs	1-week delay: 9,730.8 2-week delay: 9,728.7
Week + CovRate	Community + House	The effect of the intervention is modulated by coverage rate	9,790.1

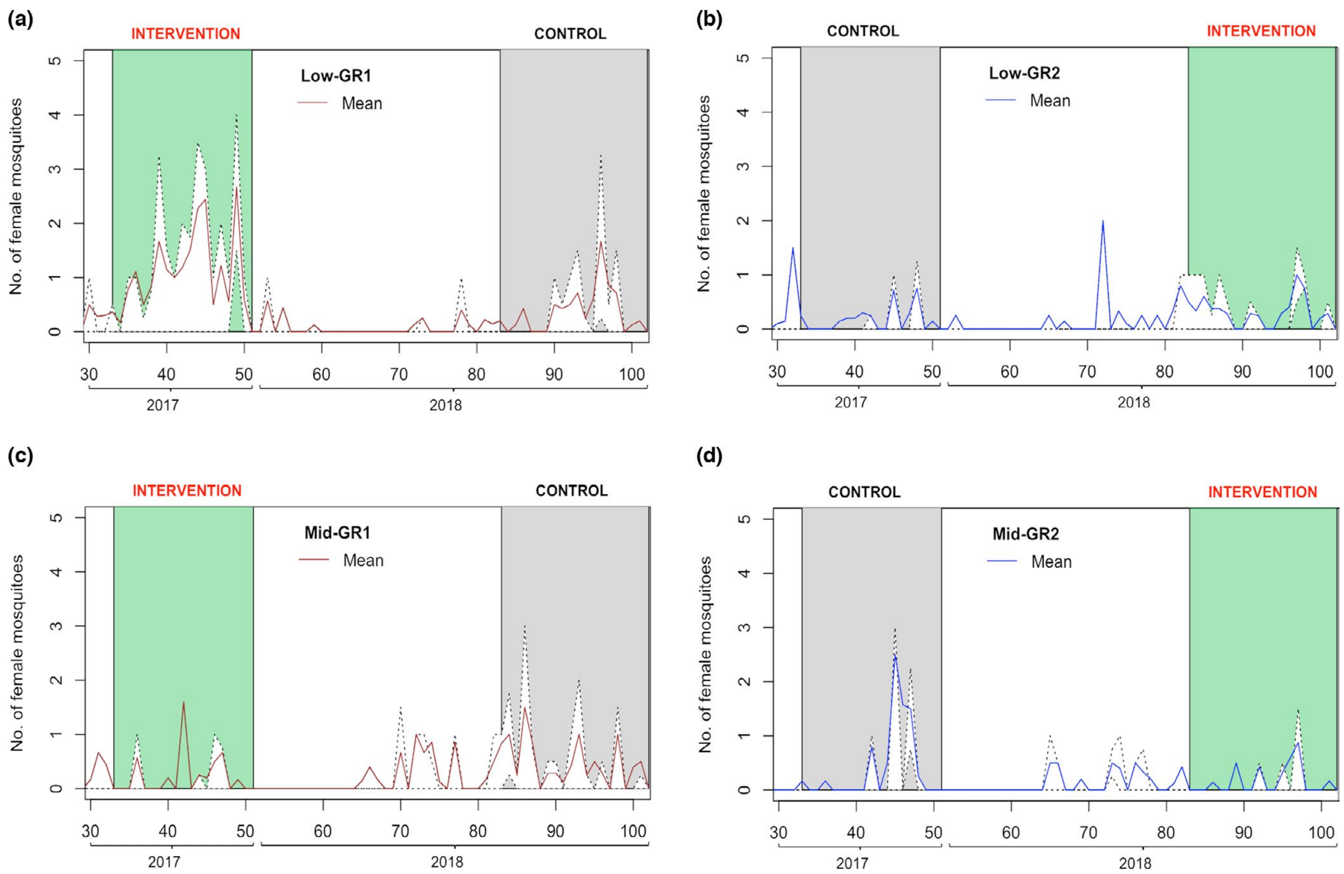

FIGURE 2 Average number of female *Aedes aegypti* per SAGO trap per week for indoor traps in low- and middle-income communities during the surveillance period of 2017 and 2018. The doted black line represents the 25%–75% percentile of the mean. (A–B) Low-income communities for Group 1 (GR1) and Group 2 (GR2) respectively. (C–D) Middle-income communities for GR1 and GR2 respectively. Green frames show the time period in which the AGO intervention took place in each corresponding group (GR1 = intervention 2017, GR2 = intervention 2018), while the grey frames show the time period when the intervention took place in the other group (GR1 = control 2018, GR2 = control 2017)

and December retrieval) for a total of 425 assessments, of these 4% failed (broke, lost or tipped over) in October and 3.4% in December. We detected that 3.1% (13/425) had either larva, pupae and/or adults inside the traps.

The community participation for the 2018 intervention period increased to 88.8% (48/54 houses) in low- and 66.3% (69/104 houses) in middle-income communities (Table 2). A total of 297 IAGOs were deployed, 120 in low-income communities with an average of 26.3 (*SD* = 4.4) Culicidae/IAGO/2 months, and 177 in middle-income communities with an average 20.9 (*SD* = 3.0) Culicidae/IAGO/2 months. We carried out 594 assessments of which 4% failed in October and 3.4% in December. We detected 2.0% of the traps having larva–pupae and/or adult mosquitoes (see Appendix S1 AGO operationalization).

3.3 | Evaluating the IAGO as a control tool

The GLMM analysis showed that the short effect models with a delayed impact on the intervention had the best fit for our data (1-week lagged AIC_{weight} = 0.30; 2-week lagged AIC_{weight} = 0.31), with the 2-week lagged model having the best fit with an AIC of 9,728.7. We observed significant effects for the two-way interaction terms (socioeconomic status by trap placement; year by treatment phase) and even though temperature was non-significant this covariate did improve the overall fit of the model when included (see Appendix S2). We were able to observe that given the conditions of 2018, the deployment of the IAGOs resulted in a suppression effect of 0.23 (77% reduction; 95% CI 65%–83% reduction) female *A. aegypti* relative to the pre-treatment phase (Table 3).

3.4 | Evaluating the coverage of IAGOs

In 2017, we deployed 3.6 IAGOs/ha (*SD* = 1.4) with an average of 1.6 IAGOs/house (*SD* = 0.4). In 2018, we were able to increase the deployment to 4.7 IAGOs/ha (*SD* = 1.1) with an average of 1.9 IAGOs/house (*SD* = 0.3). Due to this variability, we evaluated how trap coverage or density, measured as CovRate modulated the abundance of female *A. aegypti* in the LRGV. The GAMM analysis showed that the smoothing spline penalizing effects for the covariates of week (χ^2 = 573.0, edf = 8.67, $p < 0.001$) and CovRate (χ^2 = 27.3, edf = 2.97,

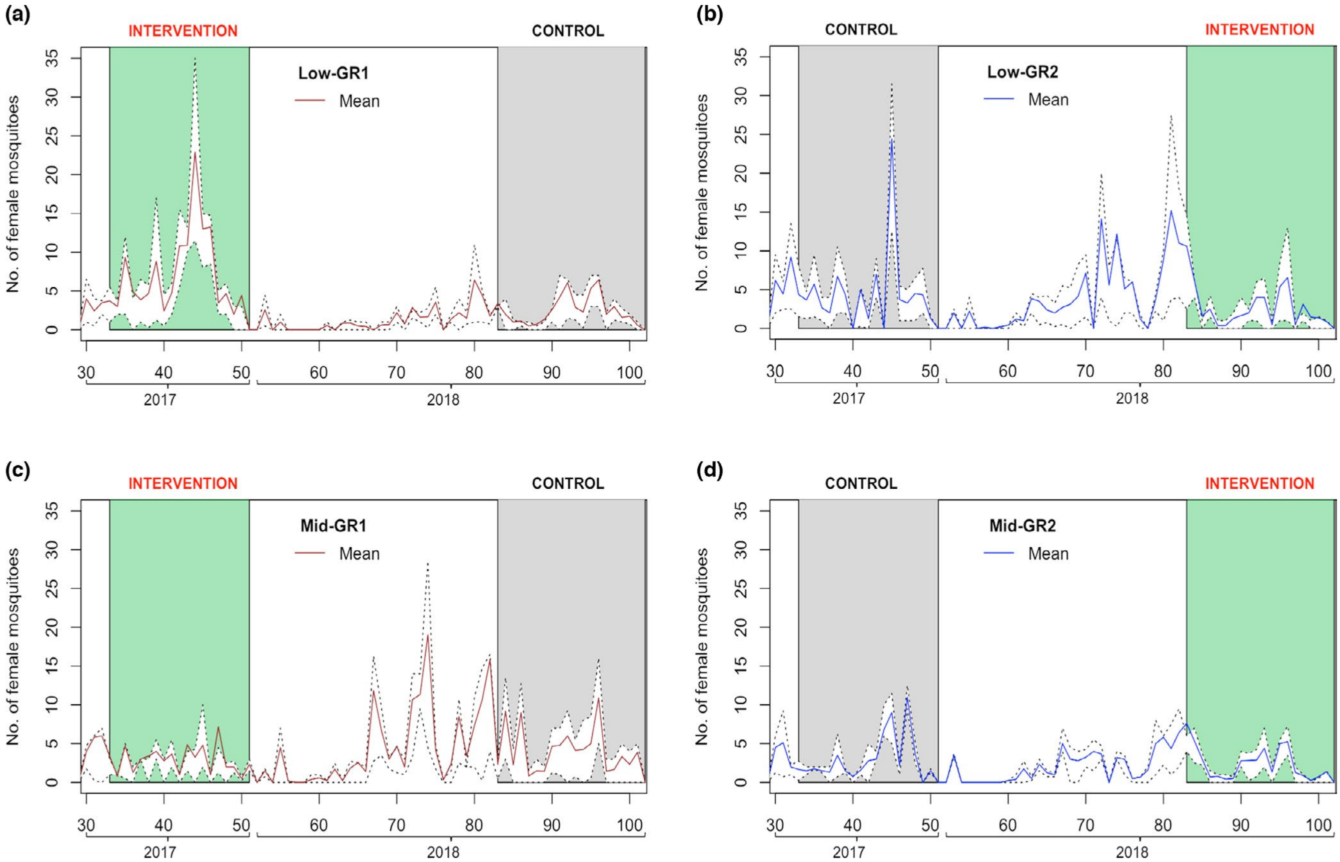

FIGURE 3 Average number of female *Aedes aegypti* per SAGO trap per week for outdoor traps in low- and middle-income communities during the surveillance period of 2017 and 2018. The doted black line represents the 25%–75% percentile of the mean. (a, b) Low-income communities for Group 1 (GR1) and Group 2 (GR2) respectively. (c, d) Middle-income communities for GR1 and GR2 respectively. Green frames show the time period in which the AGO intervention took place in each corresponding group (GR1 = intervention 2017, GR2 = intervention 2018), while the grey frames show the time period when the intervention took place in the other group (GR1 = control 2018, GR2 = control 2017)

TABLE 2 Total mosquitoes (Culicidae) captured from the IAGOs during the October reset December retrieval

Group	Socioeconomic status	Community	Community participation (%)	Trap total (Trap/ha)	October total (Culicidae/AGO)	December total (Culicidae/AGO)
GR1	Low	Balli	18/33 (55)	98 (21.8)	1,930 (37.8)	2,956 (62.9)
		Cameron	35/74 (47)	180 (21.7)	2,724 (33.2)	4,760 (48.6)
	Middle	Christian Ct.	13/26 (50)	78 (15)	1,000 (25.6)	1,146 (29.4)
		Rio Rico	11/17 (65)	69 (17.7)	885 (25.3)	664 (19.5)
GR2	Low	Mesquite	26/32 (81)	138 (36.3)	1,407 (21)	2,475 (34.9)
		Chapa	19/22 (86)	101 (28.8)	816 (17)	1,578 (30.3)
	Middle	La Vista	36/52 (69)	175 (25.7)	1,173 (13.8)	1,775 (19.7)
		La Bonita	33/52 (63)	180 (33.9)	1,985 (20.5)	2,485 (29.9)

$p < 0.001$), were statistically significant and improved the overall fit of the model (with CovRate spline AIC = 9,790; without CovRate spline AIC = 13,773).

The smooth spline effect for week shows a clear seasonal pattern for female *A. aegypti* in the LRGV (Figure 4a). We observe three distinct peaks of higher female abundance at weeks 17, 30 and 44, with decreases in weeks 1–8, 31–16 and 45–51. The smooth spline effect of CovRate shows an increase from 0 IAGO/house (10.7 females; *SE* = 1.1) to 1 IAGO/house (17.1 females; *SE* = 1.8), afterwards we observe a steady decrease in female abundance as IAGO coverage increases (Figure 4b). If all other variables are held constant, at a max coverage of 2.7 IAGOs/house (4.6 females; *SE* = 0.5) areas had 2.3 times less outdoor abundance than areas with 2 IAGOs/house (10.7 females; *SE* = 1.1) and 4 times less abundance than areas with 1

TABLE 3 Main effects statistics for the best fit 2 weeks delayed generalized linear mixed model for female *Aedes aegypti* abundance in South Texas (NB type 2)

Variable	Exp (estimate)	Estimate	*SE*	95% CI	*Z* value	*p*-value
Intercept		−4.401	0.43	−5.26 to −3.54	−10.06	<0.001
Socioeconomic status (Middle)	0.51	−0.661	0.51	−1.66 to 0.34	−1.29	0.196
Trap Placement (Out)	**11.10**	**2.407**	**0.08**	**2.24 to 2.57**	**28.78**	**<0.001**
Year (2018)	1.07	0.067	0.13	−0.20 to 0.34	0.48	0.627
Treatment Phase (Control)	0.87	−0.138	0.22	−0.57 to 0.30	−0.62	0.537
Treatment Phase (Intervention)	**2.39**	**0.872**	**0.22**	**0.43 to 1.32**	**3.85**	**<0.001**
Temperature	1.01	0.009	0.01	−0.00 to 0.02	1.78	0.074
Socioeconomic status (Middle) * Trap Placement (Out)	**1.45**	**0.375**	**0.14**	**0.10 to 0.64**	**2.75**	**0.005**
Year (2018) * Treatment Phase (Control)	1.34	0.292	0.20	−0.10 to 0.68	1.45	0.145
Year 2018 * Treatment Phase Intervention	**0.23**	**−1.428**	**0.18**	**−1.79 to −1.06**	**−7.64**	**<0.001**

*Indicates an interaction between effects. Variables in bold are considered statistically significant.

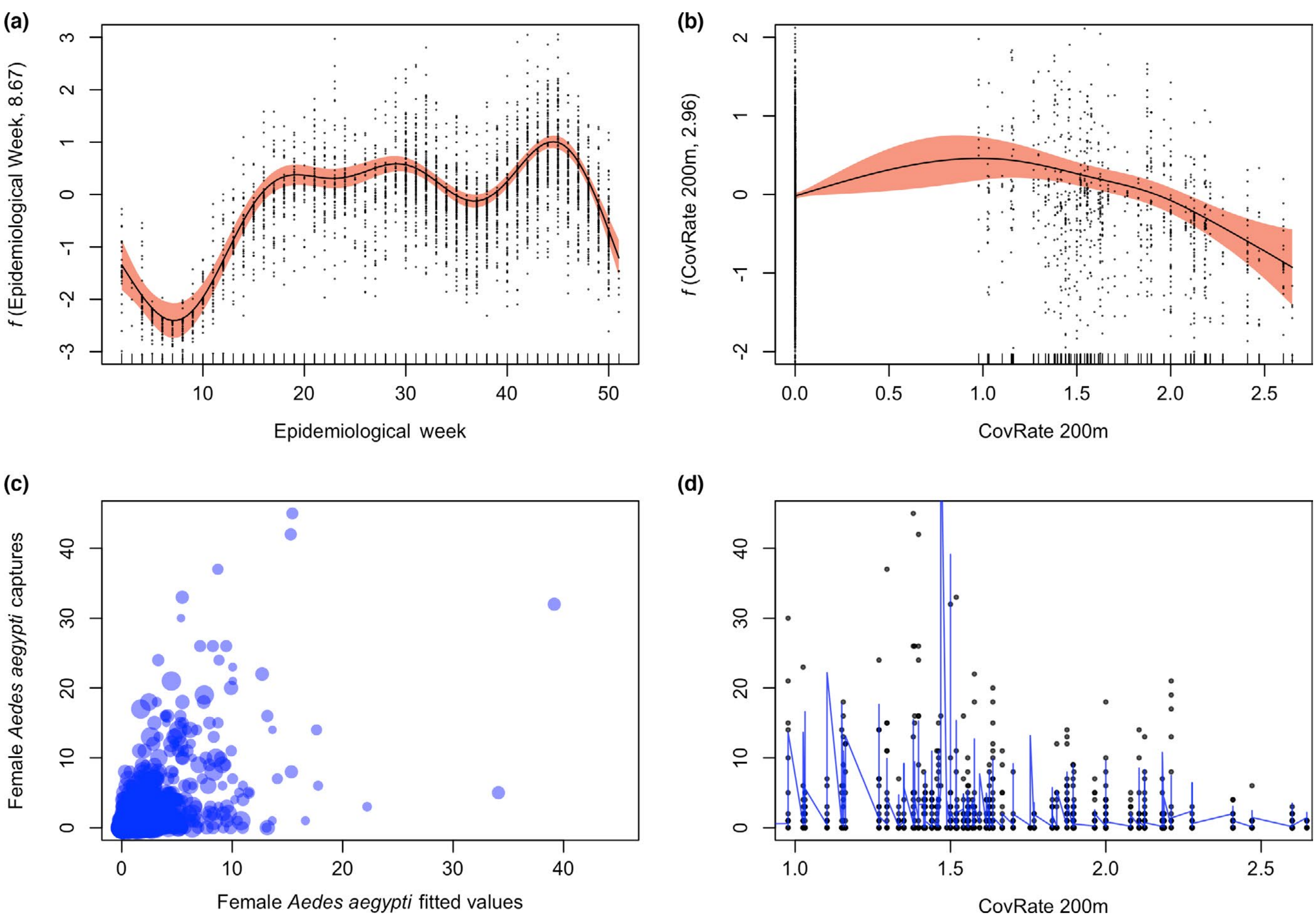

FIGURE 4 Estimated smoothers and fitted values of the negative binomial generalized additive mixed model (GAMM) for female *Aedes aegypti* abundance in the LRGV. (a) The smoothing spline effect of week with partial residuals. (b) Smoothing spline effect of CovRate (total no. of AGOs/total no. of houses in a 200 m radius) with partial residuals. (c) Observed female mosquito abundance versus fitted GAMM values with dot size proportional to coverage. (d) Fitted values (solid blue line) for the mean obtained by the GAMM, filled dots = observed values

IAGO/house (see Appendix S2 Table S24). The fitted values obtained through the GAMM model are shown in Figure 4c,d. Interestingly, at an estimated coverage of 1.4–1.5 IAGOs/house we observed an increase in abundance for the fitted values (Figure 4d).

4 | DISCUSSION

The AGO has been shown to work as a control tool in Puerto Rico when combined with a larval source reduction campaign (Barrera et al., 2014). We conducted a CRXO AGO intervention in the LRGV region of South Texas, to evaluate the effects of this trap as a stand-alone control tool for reducing the relative abundance of female *A. aegypti*. Our results show that the AGO was able to suppress mosquito populations in the region, but modulated by the effect of trap coverage in an area.

The GLMM models suggest that the effect of the intervention was lagged, with a suppression effect observed in the intervention communities of 2018 (77% reduction), the time period with highest IAGO coverage (i.e. trap density) in the study. This level of suppression has also been observed in Puerto Rico where AGO coverage was high (Barrera et al., 2014). We did not observe a statistically significant reduction in the mosquito population for the intervention communities in 2017, the time period with our lowest IAGO coverage. The GAMM model suggests that IAGO coverage modulates the response of mosquito population to our intervention, higher female *A. aegypti* abundance at lower coverage and suppression at higher coverage, with a strong decrease after two IAGOs/house is achieved. Shifts in female *A. aegypti* abundance caused by AGO coverage have been previously observed (Barrera et al., 2019). However, this shift in increase at lower coverage is something that has not been previously reported but deserves more attention.

The importance of a high coverage for successful mosquito population suppression has been observed for other vector control tools such as insecticide-treated nets (ITNs; Hawley et al., 2003). In the case of ITNs a high coverage distribution in communities has been shown to significantly reduce malaria transmission by *Anopheles gambiae*, even decreasing mosquito abundance in housing compounds from control villages without ITNs but near to intervened ITN villages (Hawley et al., 2003). Our results suggest that similar patterns might happen with IAGO coverage, as reductions in *A. aegypti* populations were only achieved when there were more than two IAGOs in each household within the 200 m radius buffer area surrounding the SAGO. We assume this is the distance a mosquito might move before reaching any given focal house, based on our dispersal study in the area (Juarez et al., 2020). This result suggests that ensuring more than two IAGOs for each household in a community can render IAGOs into populations sinks (Pulliam, 1988). However, because it is unlikely for 100% of homes in a community to provide permission, the number of IAGOs per household would need to increase accordingly. Moreover, the concave down shape of the function relating mosquito abundance and IAGO coverage also suggests that less than one IAGO per house in the same 200 m radius might have the opposite effect. Based on previous *A. aegypti* studies we believe that a low density of IAGOs in the 200 m radius area surrounding a house might decrease the impact of density-dependent regulation in mosquitoes, as IAGOs might reduce oviposition pressure in other already colonized larval habitats, which are not preferred as oviposition habitats (Zahiri & Rau, 1998). This in turn might have an impact similar to external larval mortality, which has been experimentally shown to increase mosquito size and fecundity (Wilson et al., 1990). Fecundity is a life-history trait whose increases are associated with transient outbursts of adult mosquitoes, as suggested by mathematical models fitted to *A. aegypti* field data (Chaves et al., 2014). Thus, our results make clear that spatial coverage requires a proper evaluation and consideration when designing and evaluating intervention control activities. We propose that future AGO interventions should consider the coverage rate based on the density of IAGOs within an area, especially in communities where property sizes may vary widely.

The AGO intervention is one form of vector control that requires active cooperation by community members, and this study emphasizes the importance of achieving high levels of social integration and cooperation by households. Community-based research, or bottom-up vector control, is becoming more common and different strategies are being utilized in different settings (Pennington et al., 2021). This study demonstrates that achieving high AGO coverage takes considerable resources and, in some communities, might be cost-prohibitive as an operational vector control tool. Our survey of homeowners in this region reported that 95% of the homeowners would support the AGO intervention if the traps and maintenance were free; support declined to 25% if the homeowner was required to purchase the AGO and conduct the maintenance (Juarez, Garcia-Luna, et al., 2021). It also shows variation in receptivity to the AGO intervention among communities, which will likely occur elsewhere as well. In the LRGV, low-income communities along the US–Mexico border (a.k.a. '*Colonias*') usually have underserved populations of Hispanic heritage with a historic record of exclusion from decision making in access to essential resources, as observed with water access rights (Jepson, 2012; Jepson & Vandewalle, 2016). In the '*Colonias*' problems of vacant lots from absentee landowners create issues of social cohesion that undermine both government credibility and the ability of communities to organize and implement, or join, concerted actions for their own wellbeing (Ward & Carew, 2000). With researchers observing that '*Colonias*' are a hard-to-reach minority group (Mier et al., 2008).

Some limitations of the study were that we did not conduct a concurrent larval source habitat reduction campaign, as in the trials done in Puerto Rico (Barrera et al., 2014; Sharp et al., 2019). We were able to observe that most of these communities had a large number of containers which would have provided more oviposition habitat for gravid females, and thus reduce the effectiveness of the AGO units. Unfortunately, a community source reduction campaign was not a viable option given resource constraints for this study. We observed that even when containers were removed from properties by homeowners due to flooding events in the region, they would often be quickly replaced by additional container habitat. Additionally, our intervention periods were only 4 months in comparison to those in Puerto Rico that lasted between 1 and 2 years (Barrera et al., 2014). In the LRGV, *A. aegypti* populations peak between September and November which is also when human cases of DENV, CHIKV and ZIKV have occurred (Martin et al., 2019). In this context, an intervention which is ephemeral, only targeting the peak period of risk, would be ideal. We interpret our results carefully since most of the communities had less than the recommended community participation of 80% of homes with three AGO units (Barrera et al., 2014), which make comparisons with other AGO intervention studies difficult.

The development of novel vector control tools in our fight against *A. aegypti* and associated diseases is more important than ever, especially when in 2019 a sixfold increase was observed in dengue-related deaths when compared to 2018 in the Americas (PAHO, 2019). Nonetheless, such tools still need to be tested across diverse local settings. In this study we observed that AGOs were an effective stand-alone control tool only in those communities of South Texas with high coverage rate. We believe that if coupled with a larval habitat source reduction campaign and sustained high coverage rate it may prove to be an efficient method of control for *A. aegypti*, but this necessitates more resources to execute which is often cost-prohibitive in low-income settings.

ACKNOWLEDGEMENTS

We are grateful to the residents of our study locations in the Lower Rio Grande Valley who collaborated with us to conduct this intervention study in their neighbourhoods. We thank Ester Carbajal, Edwin Valdez, Courtney Avila, Cynthia Flores, Juliet Vallejo, Damion Blanchard and Daniel Zamarripa for their assistance in the field. We appreciate the support from Roberto Barrera and Ryan Hemme for providing AGO traps in 2016 to initiate baseline surveillance and for their constructive review of the manuscript. We thank Silvana Caravantes for the AGO trap illustration. This work was supported by the National Institutes of Health R21AI128953 and Cooperative Agreement Number U01CK000512 (G.L.H. and I.B.-V.), funded by the Centers for Disease Control and Prevention. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the Centers for Disease Control and Prevention or the Department of Health and Human Services.

CONFLICT OF INTEREST

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

AUTHORS' CONTRIBUTIONS

G.L.H., I.B.-V., J.G.J. and M.C.I.M. conceived the ideas and the designed methodology; J.G.J., S.M.G.-L. and E.M. collected the data; J.G.J., L.F.C., M.C.I.M. and G.L.H. analysed the data; J.G.J., L.F.C. and G.L.H. led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

Data available via figshare Digital Repository https://doi.org/10.6084/m9.figshare.13053986.v3 (Juarez, Chaves, et al., 2021).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Juarez, J. G., Chaves, L. F., Garcia-Luna, S. M., Martin, E., Badillo-Vargas, I., Medeiros, M. C. I., & Hamer, G. L. (2021). Variable coverage in an Autocidal Gravid Ovitrap intervention impacts efficacy of *Aedes aegypti* control. *Journal of Applied Ecology*, 58, 2075–2086. https://doi.org/10.1111/1365-2664.13951