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Information to Act: Household Characteristics are Predictors of Domestic Infestation with the Chagas Vector *Triatoma dimidiata* in Central America

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Abstract. The interruption of vectorial transmission of Chagas disease by *Triatoma dimidiata* in central America is a public health challenge that cannot be resolved by insecticide application alone. In this study, we collected information on previously known household risk factors for infestation in 11 villages and more than 2,000 houses in Guatemala, Honduras, and El Salvador, and we constructed multivariate models and used multimodel inference to evaluate their importance as predictors of infestation in the region. The models had moderate ability to predict infested houses (sensitivity, 0.32–0.54) and excellent ability to predict noninfested houses (specificity higher than 0.90). Predictive ability was improved by including random village effects and presence of signs of infestation (insect feces, eggs, and exuviae) as fixed effects. Multimodel inference results varied depending on factors included, but house wall materials (adobe, bajareque, and palopique) and signs of infestation were among the most important predictive factors. Reduced models were not supported suggesting that all factors contributed to predictions. Previous knowledge and information from this study show that we have evidence to prioritize rural households for improvement to prevent house infestation with *Triatoma dimidiata* in Central America. House improvement will most likely have other health co-benefits.

INTRODUCTION

Chagas disease is a neglected tropical disease endemic to the Americas where it is estimated that 10 million people are infected.[1] It is caused by the protozoan parasite *Trypanosoma cruzi*, which is transmitted by triatominae insect vectors. *Triatoma dimidiata* is the most important Chagas insect vector in central America and reducing the domiciliary infestation with this insect is one of the three main goals of the Central American and Mexico Control Initiative (IPCAM), which has the goal of interrupting Chagas disease transmission.[2] The traditional approach of residual insecticides application has shown mixed results in Central America. In some localities, it has successfully reduced infestation; however, in other localities, *Triatoma dimidiata* rapidly reappeared in houses following insecticide application.[3,4] Recent studies suggest that for the most problematic localities, consecutive rounds of spraying should occur within 1 year to reduce the odds of reinfestation,[5] a practice that could be unsustainable in developing countries. Repeated rounds of spraying could also lead to reduced susceptibility of insect populations to insecticides.[6] Since the description of Chagas disease, it has been known that rustic or deteriorated human domiciles provide conditions that allow triatomine infestation and colonization,[7] increasing the contact between humans and vectors and the risk of parasite transmission. Improving the domicile could provide long-term protection against the insect vectors by reducing infestation and preventing reinfestation.[7–10]

The risk factors associated with the odds of *Triatoma dimidiata* infestation have been studied across the distribution of this species.[11–19] In Yucatan, factors from outside of the houses, such as proximity to streetlights, proximity to vegetation, and the presence of animals or rock piles in the peridomicile, are risk factors that attract non-domiciliated *Triatoma dimidiata* into houses.[12,16] In central America, where *Triatoma dimidiata* is considered domiciliated, the type of house construction materials and their quality are very important risk factors for infestation. A study conducted at the village level in two departments of Guatemala found that the type of wall, roof, and floor was associated with house infestations, but the degree and direction of the associations varied between the two departments.[14] Studies conducted at the household level in the Guatemalan departments of Jutiapa[11,15] and Chiquimula[13] found that poor sanitary conditions or a disorganized house, dirt floors, walls made of rustic materials (adobe, bajareque), and low-quality or nonexistent wall plastering, tile roofing, dog density, mice presence, and coffee trees around the house are factors associated with increased odds of *Triatoma dimidiata* presence. The presence of triatomine-like feces in the house increased the odds of live infestation in the Chiquimula study.[13] A study in Costa Rica also pointed to house conditions (poor sanitation, dirt floors, and tile roofs) as the most important risk factors for house infestation.[19] This evidence supports house construction materials and house cleanliness as relevant factors for *Triatoma dimidiata* infestation in central America.

Various studies at different scales have shown that improvements to the walls of rural houses to eliminate the cracks and crevices where the insects hide could drastically reduce or eliminate infestation.[20–22] However, the implementation of house modification as a control strategy faces challenges including high costs and low community participation. Following the principles of the ecosystem approach to human health research or Ecohealth,[23] a pilot study in two villages in Jutiapa, Guatemala[15,24,25] (2004–2009) evaluated the use of inexpensive, locally derived materials to make a longer-lasting plastering mix to repair cracked walls. In addition, social scientists worked with the community to achieve participation in the improvements. Homeowners self-reported making regular repairs to the wall plastering in the 2 years

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prior to the beginning of the study. Because plastering was a common practice in the study area, many people were receptive to the improved plastering mix.[24,25] Within the first 2 years of the pilot study, all the houses in the village were sprayed with insecticide and walls were improved in a fraction of them. The percentage of houses with good quality complete plastering increased by 21% and 13% in the two Ecohealth-intervention villages; one control village showed a 4% decline and another showed an 9% increase in good quality complete plastering.[24] After 5 years of interventions, the percentage of *Triatoma dimidiata* feeding on humans dropped from 38% to 7% and *Trypanosoma cruzi* infection in *Triatoma dimidiata* dropped from 49% to 16% in one intervention village,[26] whereas in the other intervention village, the number of *Triatoma dimidiata* dropped drastically and it was not possible to obtain an estimate of percent of insects feeding on humans. Infestation levels in that village have remained under the 5% threshold set by the Guatemalan Ministry of Health for insecticide application[27] and also under the suggested threshold of infestation (8%) at which *Trypanosoma cruzi* transmission becomes unlikely.[28]

Central American ministries of health are interested in introducing low-cost longer-lasting plastering mix to repair cracked walls in areas with domestic infestation of *Triatoma dimidiata* to help with regional control goals.[1] As mentioned before, there are known housing factors that are associated with house infestation with *Triatoma dimidiata*. Here we present the results of a three-country project studying the relative importance (RI) for the prediction of infestations of known house factors to determine the houses most at risk and of need of improvements. Only two previous studies of risk factors for *Triatoma dimidiata* have evaluated the predictive ability of the models proposed.[12,14] Data were collected from villages in Chiquimula, Guatemala; Texistepeque, El Salvador; and Intibuca, Honduras. This was a "scaled-up" Ecohealth project that followed a similar outline as a pilot project conducted in Jutiapa, Guatemala.[24,25]

We formulated multivariate logistic regression models and the variables included in the models constituted our hypothesis of the factors that predict infestation in this region. Given that this was not a controlled study but an observational study, and the design was not balanced, we decided to use multimodel inference[29] to estimate the RI of the factors to predict infestation, instead of using tests to identify significant variables associated with infestation. In the process, we explored and compared reduced models representing subsets of the factors in the hypothesis, and evaluated model selection uncertainty. We calculated the sensitivity, specificity, and positive and negative predictive values of the model predictions. Previously available information and the results of this study allow us to propose that we have good evidence to take more action[30] and promote house improvements as a control measure in the region.

MATERIALS AND METHODS

Study areas. The study was conducted in 11 villages in three central American countries (Figure 1). A total of 2,681 houses and other types of structures (such as schools, community centers, churches, and storerooms) were surveyed for triatominae presence. In Guatemala, 1,140 structures were surveyed in five villages in Olopa, Chiquimula: El Amatillo (215), El Cerron (205), El Guayabo (302), El Paternito (138), and La Prensa (280). In Honduras, 613 structures were surveyed in four cantones in San Marcos de la Sierra, Intibuca: Centro San Marcos (202), Las Delicias (102), San Jose (117), and San Luis (192). In El Salvador, two cantones were surveyed in Texistepeque: El Chilcuyo (248) and

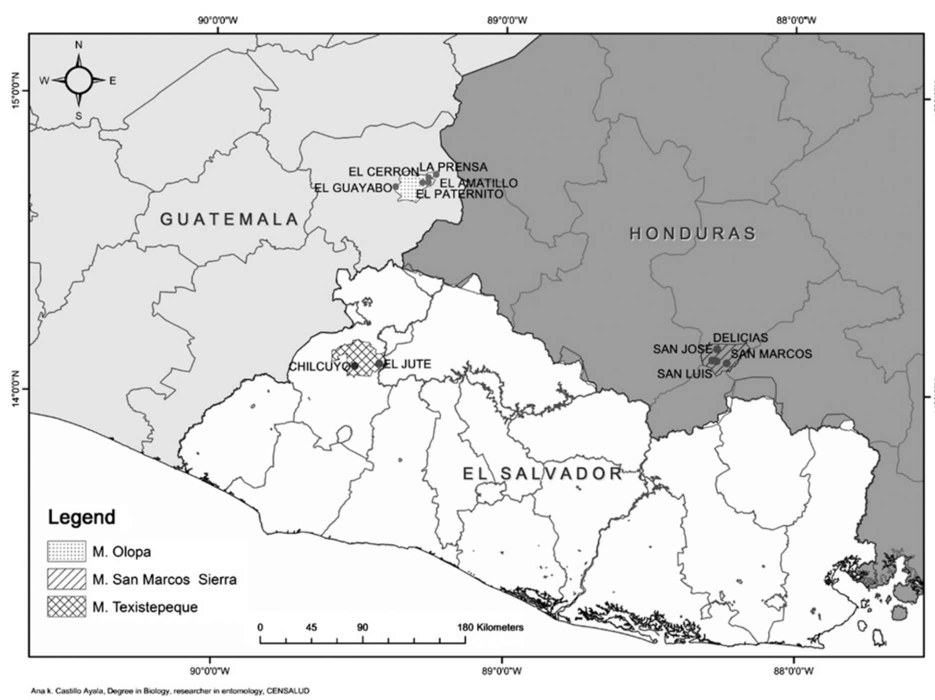

FIGURE 1. Study area: villages in Olopa, Chiquimula, Guatemala; San Marcos de la Sierra, Intibuca, Honduras; and Texistepeque, Santa Ana, El Salvador.

El Jute (680). The cantones in Honduras are subdivided into villages, and in El Salvador the cantones are subdivided into caserios, but we consider the canton a geographic unit equivalent to the villages in Guatemala for the purpose of the analysis. Study areas were selected on the basis of reported persistent triatomine infestation and accessibility. Before conducting surveys in the villages, meetings were held with local authorities to introduce the project and ask for their collaboration.

Socioeconomic and entomological surveys. Each country had a different team that conducted entomological and house construction surveys. In Guatemala, the team was composed of personnel from Escuela de Biologia, San Carlos University, and from the local Ministry of Health Office of Vector-Borne Diseases. In Honduras, the team included personnel of the Ministry of Health (Chagas Program). In El Salvador, the team included personnel from the Center for Health Research and Development, University of San Salvador, and the Ministry of Health (Vector control program). In all countries, each house or structure was surveyed by two people, one interviewer and one insect collector. After asking for permission to conduct the survey, the collector started a triatomine search in the house (35–45 minutes) using flashlight and forceps; at the same time, the interviewer filled out a questionnaire with a member of the household.

The structured questionnaire consisted of 71 items. Sixty two of the items were multiple choice questions that were asked to an adult person in the household, although in a few cases children from 7 to 17 years old also contributed to the interviews (this was the case in 7.36% of houses in Guatemala, 3.22% of those in Honduras, and 6.19% of those in El Salvador). These questions included family and socioeconomic factors (14 items), household practices (25), domestic animals (4), and knowledge about Chagas disease (19). The remaining items (9) were related to house structure and construction materials (predominant wall material, predominant plastering conditions, number of windows, and signs of animals inside the house) that were filled out based on observations by the interviewer. Most of the interviewers had extensive experience in Chagas surveys. Workshops were held before the surveys to inform the interviewers of the criteria they should use to fill out the questionnaire. For example, house hygiene was a subjective assessment of the overall cleanliness of the home by the surveyor. A house with "bad" hygiene was characterized by presence of garbage, cluttering of clothes or other objects on top of the bed, beds not made, lack of floor sweeping, presence of animals and/or animal feces inside the house, spider webs inside the house, and lack of running water or a latrine/bathroom. Similarly, "bad" bed hygiene was recorded if the bed was not made, there was cluttering on or underneath the bed, dirt on the bed, and/or animals sleeping on the bed or under the bed. Wall plastering condition was considered "good" if it was smooth and had no cracks or crevices, or if the house was a brick house then the plastering was classified as good. "Bad" plastering consisted of no plastering in an adobe, bajareque or palopique home, or incomplete, cracked, and crumbling plastering.

The majority of surveys were conducted between the months of August and October 2011. Some surveys had to be completed in the months of November and December 2011 in Guatemala and El Salvador because of bad weather. The insects collected were kept alive and transported to laboratories in each country for preservation and future analysis.

Ethics statement. Informed consent was obtained from all human adult participants and from parents or legal guardians of minors. This project received ethical clearance from the Ministry of Health in Guatemala, the San Carlos University bioethics committee, and the Panamerican Health Organization.

Data analysis. The data for the present study consisted of a binomial response variable, *Triatoma dimidiata* presence/absence, and a set of categorical or integer variables measured for each house or structure during the survey. Multivariate logistic regression analysis was used to study how the odds of *Triatoma dimidiata* presence relate to each variable, keeping all other variables constant. We used 25 variables selected a priori (full model, Table 1), because we have previous knowledge of variables that increase the odds of infestation[15] and our survey was designed to gather information on specific factors. A workshop was conducted with all research team members to select the subset of 25 variables that constituted our hypothesis of the factors that best explain house infestation in the central American region under study. Some categories for each factor were collapsed to avoid small numbers of observations (see coding in Table 1). All houses that had missing information for one or more of the factors included in the hypothesis were removed and the resulting database consisted of 2,063 houses and other structures. This step was necessary to make models comparable when using information criteria.

The analysis followed some of the recommendations in the work of Bolker and others[31] on the use of generalized linear mixed models in ecology. Four models were fitted (see below) and compared using the Akaike Information Criterion (AIC) to determine which models best fitted the data and the model with best predictive accuracy, among those considered. In addition, we tested the contribution of villages as a random effect and of "signs of infestation" (Table 1, factor no. 24) as a fixed effect. The villages where the surveys were conducted are factors that introduce geographical variation but the effect of particular villages to the response variable was not of interest. The signs of infestation cannot be considered a causal factor of infestation but a consequence of it, however, previous models have found that the presence of these signs is associated with infestation[13] and it was of interest to test the contribution of this factor to make predictions of live infestation. Given that information was lacking as of the age of the signs (fresh or old feces, recent or old exuviae, and hatched or unhatched eggs) to possibly discern between old or recent infestations, we considered them all in unity; the variable house age was included in the model to control for time effects. The fitted models were as follows:

Model 1: infestation (yes/no) ~ intercept + 24 fixed effects
Model 2: infestation (yes/no) ~ intercept + 25 fixed effects (includes signs of infestation)
Model 3: infestation (yes/no) ~ intercept + 24 fixed effects + village random effect
Model 4: infestation (yes/no) ~ intercept + 25 fixed effects + village random effect

The multivariate logistic regression models (Models 1 and 2) were fitted using the *glm* function of the stats package in R,[32]

Table 1
House factors included in the full model and the codification of their values

House factor	Coding
1. Bed hygiene	Good, bad
2. Bird nests inside	Yes, no
3. Chicken coop location	No chicken coop, chicken coop outside the house, chicken coop inside or immediately adjacent to house*
4. Cluttering (boxes, clothes) in bedroom	Yes, no
5. Construction materials piles by type	No materials, yes wood and ceramic tile*, yes adobes and clay tiles*
6. Dark room	Yes, no
7. Education level	Primary, secondary, high school to college*, none
8. Firewood piles by location	No firewood, firewood outside the house, firewood inside or immediately adjacent to house1
9. Floor type	Dirt, other not dirt*
10. Grain storage in house	Yes, no
11. House age	≤ 1 year, 2–6 years, ≥ 7 years
12. House hygiene	Good, bad
13. Kitchen location	Inside house, outside house, shared with other houses
14. Land for agriculture	Yes owner, yes renter, no land, other
15. Number of cats	0, 1, > 1*
16. Number of chickens	0, 1–9*, 10–19*, ≥ 20*
17. Number of dogs	0, 1, 2, > 2*
18. Number of pigs	0, ≥ 1*
19. Predominant bedroom wall plastering condition	Deteriorated, not deteriorated
20. Predominant house wall plastering condition	Deteriorated, not deteriorated
21. Predominant house wall material	Adobe, bajareque–palopique*, bricks–block–others*
22. Roof type	Aluminum sheet–cement*, clay tile–vegetal material–other*
23. Signs like feces, feathers, hair, and/or nests of animals, including mice, inside the house	Yes, no
24. Signs of infestation (insect feces, exuviae, eggs, dead insects)	Yes, no
25. Window present in bedroom	Yes, no

*Collapsed categories.

and the logistic models with village as random effect (Models 3 and 4) were fitted using the *glmer* function from the lme4 package.[33] The goodness of fit of the models was evaluated using the Hosmer–Lemeshow test. Multicollinearity was evaluated by calculating the variance inflation factors using the *vif* function from the car package in R.[34] Any collinear variables were dropped from the model. Likelihood ratio tests were used to evaluate the contribution of signs of infestation fixed effect (Model 1 versus 2) and village as a random effect (Model 1 versus 3). Given that this study has an unbalanced design, we followed the recommendation in the work of Bolker and others[31] and we did not use the *P* values provided by the linear model fitting to make inferences. We compare the models fitted using the AIC to find the model that best fits the data and the model with the best predictive ability, among those considered.

The sensitivity and specificity of the model predictions was evaluated using the method of King and others.[35] This method was used to select the threshold of presence, which is the probability value below which *Triatoma dimidiata* is considered absent and above which the species can be considered present. The threshold will be the probability value for which the higher value of the kappa statistic is obtained.[35] Five different threshold values were tested (i.e., 0.1, 0.2, 0.3, 0.4, and 0.5). After a threshold was selected, the percentage of true positives (sensitivity) and true negatives (specificity) predicted by the model, and the probability of true positives (positive predictive value) and true negatives (negative predictive value) were calculated using the *confusionMatrix* function of the caret package in R.[36]

This study also evaluated if any reduced models of Model 3 and Model 4 (initial full models with 24 or 25 variables, respectively) had similar predictive ability as the full model. The full models are only one of the 2^{24} or 2^{25} possible logistic models that could be constructed with different combinations of the variables. Inference should not be based on a single model unless there is strong support for it as the "best" model,[29] thus we conducted a multimodel inference analysis to determine if there is a single "best" model among those considered, given the data. We used the genetic algorithm available in the *glmulti* function[37,38] in the R package of the same name to 1) explore a subset of all possible reduced models; 2) compare them using the AIC; and 3) evaluate model selection uncertainty using Akaike weights. The genetic algorithm run was carried out using the default glmulti input parameters.[37,38]

The Akaike weight is the probability of a model, given the data; a model with a weight close to one can be considered the "best" model among those considered.[39] When high uncertainty was detected (no model with weight = 1), weighted model parameter estimates were calculated using the *coef* function in the glmulti package. The RI of the variables, which is the sum of the Akaike weights of all the models where the variables appeared, was obtained. High RI values indicate that the variable is frequent among models with high weights (low AIC or high predictive ability). There are no set rules on RI thresholds to define which variables are the most important and a recent study found that even variables uncorrelated with the response can show RI values as high as 0.7. Therefore, RI should not be viewed as an indication of statistical effect, but as a measure of how certain we can be that the variable is present in the "best approximating model with increasing sample size," and it should not be interpreted if the model does not fit the data.[40]

We report descriptive statistics of the variables measured in the villages and present statistics for the four models fitted to the data, the results of the likelihood ratio tests, and prediction statistics of the models. We also report on the results of multimodel evaluations: lowest AIC, number of generations before convergence, highest Akaike weights, and prediction statistics for the weighted model.

RESULTS

The houses surveyed across the three countries encompassed a broad range of conditions that could affect infestations (Table 2). In El Salvador, most houses were made of adobe (51.38%) or red brick (42.12%, see under "Others"). In Guatemala, houses were made mostly of bajareque–palopique (69.61%) followed by adobe (25.63%). In Honduras, the majority of houses were made of adobe (91.02%). The condition of wall plastering in bedrooms and the rest of the house was often deteriorated, but this was less common in El Salvador (55.00%) than in Guatemala and Honduras (higher than 80.00%). Clay tile was the predominant type of roof in El Salvador (72.38%), corrugated aluminum sheet and cement in Guatemala (89.68%), and both types were common in Honduras. Non-dirt floors (tiles and cement) were common (59.25%) in El Salvador, although dirt floors were present in 40.75% of homes. Houses in Guatemala and Honduras had predominantly dirt floors (higher than 70.00%). Self-reported house improvements in the 2 years

TABLE 2
Distribution of houses (percentage) by construction characteristics, socioeconomic characteristics, and country

	El Salvador	Guatemala	Honduras
Predominant house wall material			
Adobe	51.38	25.63	91.02
Bajareque–palopique	6.50	69.61	6.73
Others (red brick, block, wood, or aluminum sheet)	42.12	4.76	2.24
Predominant condition of bedroom wall plastering			
Not deteriorated	45.00	16.25	19.45
Deteriorated	55.00	83.75	80.54
Predominant condition of house wall plastering			
Not deteriorated	42.75	14.50	17.46
Deteriorated	57.25	85.50	82.54
Roof type			
Aluminum sheet or cement	27.62	89.68	49.13
Clay tiles, plant materials, or others	72.38	10.32	50.87
Floor type			
Dirt	40.75	87.24	71.82
Others	59.25	12.76	28.18
House improvement in the last 2 years			
Yes	33.71	29.23	19.19
Type of improvement			
Wall plastering	31.46	26.98	23.68
Roof improvement	22.85	22.62	35.53
Floor improvement	9.36	5.16	9.21
New room	27.34	34.92	15.79
Others	8.99	10.32	15.79
House ownership			
Owns	77.42	96.75	97.74
Rents	6.90	0.23	1.50
Borrows	15.68	3.02	0.75
Farm land accessibility			
Yes, owns	33.75	52.67	79.55
Yes, rents	47.12	20.42	12.98
No	17.88	26.33	7.48
Other	1.25	0.58	0.00
Main economic activity of head of household			
Agricultural worker	8.66	68.41	18.20
Self-used farmer	73.40	25.67	74.06
Self-used (non-farming)	5.52	1.74	0.25
Worker (non-farming)	2.63	1.39	1.50
Other	9.79	2.79	5.99
Other income (most common answers only)			
Chickens	72.37	8.14	45.86
Coffee (picking, greenhouses)	0.00	27.44	4.76
Pigs	1.75	1.74	0.00
Cattle and products	14.47	0.00	0.00
Highest education level of any householder			
None	12.25	22.97	18.70
Elementary	32.75	66.01	71.07
Secondary	35.75	7.66	6.73
High School or higher	19.25	3.36	3.50
Knowledge of Chagas disease vectors			
Identified *Triatoma dimidiata* and feces	1.87	8.47	17.21
Identified *Triatoma dimidiata* but not feces	62.75	57.89	70.32
Doesn't identify	35.38	33.64	12.47

prior to the survey were relatively common in El Salvador and Guatemala (about one-third of houses). Wall plastering, roof improvement, and adding new rooms to the house were the most commonly reported improvements.

Socioeconomic conditions across the three countries showed differences in the complimentary sources of income and education levels. The majority of respondents in the three countries self-reported that the head of household owned the house (higher than 75.00%). Most households in Guatemala and Honduras also reported owning land for crops, but 47.12% of households in El Salvador rented land for crops. Most heads of household were either agricultural workers or self-employed farmers. Almost 90.00% of the households in El Salvador self-reported having an additional source of income such as raising chickens and cattle. In Guatemala, one-third of the households received complimentary income from laboring in coffee plantations, whereas in Honduras, almost half of the households got additional income by raising chickens. Educational attainment was low in Guatemala and Honduras with more than 80.00% of the households reporting elementary education or no education as the highest level attained by any householder. In contrast, more than 50.00% of households in El Salvador had a member with secondary or higher education. Most of the respondents had knowledge on the Chagas disease vector *Triatoma dimidiata*, and more than 65.00% recognized either the adult or nymph stage of the insect and/or the feces.

Triatomine infestations were higher in Guatemala than in the other two countries. The percent of houses infested with live insects was highest in the villages of Guatemala (14.02–27.94%), except Amatillo (0.62%) (Table 3), and lowest in El Salvador and Honduras (0.00–9.72%). Infestation was mostly detected in houses made of bajareque–palopique or adobe in the three countries. Houses that had other signs of infestation, such as insect feces, exuviae, eggs, or dead insects, were frequently found infested with live insects, especially in Guatemala. Infested houses frequently had insects in a variety of microhabitats (bed, firewood, construction material piles, and animal nests), but the majority of insects (higher than 75.00%) were collected from the cracks in the walls made of adobe or bajareque–palopique.

The goodness-of-fit test (Hosmer–Lemeshow) supported that all the models fitted the data (Table 4). The models that included signs of infestation as a predictor showed the lowest AIC values (Models 2 and 4) indicating a highest likelihood given the data, and their predictive ability was better than Models 1 and 3; their positive predictive value indicates that 40.00% of the positive predictions made with these models were houses with live infestation. Models 2, 3, and 4 all showed an improvement in sensitivity (prediction of positive houses) and positive predictive value in comparison to Model 1. The likelihood ratio test supported that both village as a random effect and signs of infestation as a fixed effect contributed to explain the variance in the response variable (Table 4). The odds ratios (ORs) for all factors in the models are presented (Table 5). The results of Z tests are presented in Supplemental Table 1, but are not used to make inferences.

After taking Models 3 and 4 as full models for multimodel inference, the results showed that there was not a single "best" model obtained after testing reduced models. High uncertainty was found (no reduced model with weight ≥ 0.90), therefore, a reduced model is not recommended and model weighting was conducted to obtain a single model. The exponential of the weighted parameter values was calculated to obtain ORs and the RI of each variable was also calculated (Table 5). The RI indicated how often a particular variable appeared in the models with highest Akaike weights and lower AIC. When Model 3 was used as a full model, bedroom wall plastering, dark bedroom, chicken coop location, house

Table 3
Distribution (percentage) of houses infested with live insects by house conditions and country

	El Salvador	Guatemala	Honduras
Percent of infested houses by village or canton			
El Chilcuyo	6.91	–	–
El Jute	3.43	–	–
Amatillo	–	0.62	–
Cerron	–	20.55	–
Guayabo	–	16.05	–
Paternito	–	14.02	–
Prensa	–	27.94	–
Centro San Marcos	–	–	7.52
Delicias	–	–	9.72
San Jose	–	–	0.00
San Luis	–	–	9.16
Total by country	4.25	16.48	6.98
Percent of infested houses by house type			
Adobe	6.08	18.55	7.67
Bajareque–palopique	3.85	16.83	0.00
Others	2.08	0.00	0.00
Percent of houses with live insects that also had signs of infestation*, by house type			
Adobe	24.00	83.87	25.00
Bajareque–palopique	0.00	68.31	0.00
Others	85.71	0.00	0.00
Distribution of *Triatoma dimidiata* inside houses			
Mostly in wall cracks	–	76.76	82.14
Bed, firewood, construction material piles, animal nests (no walls)	–	8.41	17.86
No data	100.0	14.79	0.00

*Signs of infestation are insect feces, exuviae, dead insects, and/or insect eggs.

Table 4
Logistic regression model statistics: goodness-of-fit, prediction statistics, likelihood ratio test and multimodel inference statistics

	Model 1	Model 2	Model 3	Model 4
Full model logistic regression				
AIC	1,257	1,102	1,203	1,078
Hosmer–Lemeshow test				
χ^2	7.19	11.57	4.09	14.19
P	0.52	0.17	0.85	0.08
Prediction statistics				
Threshold of presence	0.20	0.20	0.20	0.20
Highest kappa value	0.19	0.39	0.29	0.42
Sensitivity	0.32	0.54	0.49	0.54
Specificity	0.90	0.91	0.88	0.92
Positive predictive value	0.25	0.40	0.31	0.43
Negative predictive value	0.92	0.95	0.94	0.95
Likelihood ratio test				
Residual deviance	1,175	1,018	1,119	992
Residual df	2,022	2,021	2,021	2,020
Difference vs. Model 1 (χ^2)	–	157	56	183
P	–	< 0.01	< 0.01	< 0.01
Multimodel inference				
Lowest AIC	–	–	1,177	1,042
Highest Akaike weight	–	–	0.11	0.14
Number of generations	–	–	680	640
Weighted models				
Threshold of presence	–	–	0.20	0.30
Prediction statistics				
Highest kappa value	–	–	0.28	0.42
Sensitivity	–	–	0.47	0.49
Specificity	–	–	0.88	0.94
Positive predictive value	–	–	0.31	0.46
Negative predictive value	–	–	0.94	0.94

df = degrees of freedom.

wall material, house age, and the presence of animal signs inside the house were the variables most frequently found in reduced models with a frequency of 66% or higher (RI ≥ 0.66). In comparison, when Model 4 was the full model, sings of insect infestation, house wall material, bed hygiene, house age, and floor type were the most frequent variables (RI ≥ 0.79). The prediction statistics of the weighted models were similar to those of the full models (Table 4), but the weighted Model 4 had the highest positive predictive value (0.46) indicating that 46.00% of the houses predictive to be positive by the model were in fact found infested with live insects.

DISCUSSION

This study used data from 11 communities and more than 2,000 houses in a region of central America to evaluate the ability of a set of 25 factors to predict live infestation. This study is, to the best of our knowledge, the first published assessment of the relationship between household factors and triatominae infestations in El Salvador and Honduras.

We showed that the predictive ability of models is improved when a random village effect is added, highlighting the importance of geographical spatial variation. We also found that signs of infestation improved the predictions of live infestation. All variables included in the full models contribute to predictions as no support for a "best" reduced model was found by multimodel inference, but variables differed in their importance for predictions. For full Model 3, the factors that were most frequently found in models with lowest AIC included type of bedroom wall plastering, type of house wall materials, chicken coop location, room darkness, house age, and animals inside the house. For full Model 4, the factors included type of house wall materials, degree of bed hygiene, floor type, house age, and signs of insect infestation (insect feces, exuviae, dead insects, and/or insect eggs). Odds of infestation increased with bad wall plastering, rustic wall materials (adobe, bajareque–palopique), older houses (higher than 6 years), animals inside the house, presence of a chicken coop, dirt floors, and signs of triatominae insects inside the house. Having a not-dark home contributed to decreasing the odds of infestation.

Descriptive data also supported the high importance of the presence of signs of infestation and rustic wall construction materials as risk factors. Many of the houses that had insect signs were also infested and the cracks and crevices in rustic walls constituted the most common intradomiciliary habitat for insects. This is why the low RI of deteriorated wall plastering quality of the house as a whole, as revealed by the multimodel inference approach, was surprising. This might be because a house was considered to have deteriorated plastering if at least one of the walls was deteriorated; this could have overestimated the proportion of houses with deteriorated plastering and there might not have been enough variation in the data to detect an effect.

Even though our analysis used multimodel inference instead of statistical significance, our observations generally agree with previous studies in Guatemala. A previous study found increased odds of infestation in villages with a high proportion of houses made of adobe in Baja Verapaz and in villages with high proportion of houses made of stick and mud (bajareque) and dirt floors in Jutiapa.[14] In Chiquimula, unplastered bajareque walls, dirt floors, and the presence of triatomine-like feces in the house increased the odds of infestation.[13] Other studies in Jutiapa found that walls made of adobe with deteriorated or no plastering were associated with *Triatoma dimidiata* presence.[11,15] It can be noted that these variation in significance of association of factors from one place to the other could be a consequence of the lack of a balanced design. For instance, Jutiapa and Baja Verapaz might not have similar frequency of adobe and bajareque–palopique homes and this could affect the associations found. In this study, we did not have a balanced design to compare between countries; therefore, we used all the data in the same analysis and included location as a random effect.

The predictive ability of the full models and the weighted models was similar to the performance of previously published models of triatominae infestation. A study conducted in Yucatan, Mexico, presented a model with moderate sensitivity (0.41) and excellent specificity (0.90) for the prediction of *Triatoma dimidiata*-infested houses.[12] Another study at the village level in Guatemala found thresholds of presence at kappa of 0.56 for Baja Verapaz (sensitivity, 0.76; specificity, 0.80), and kappa of 0.51 for Jutiapa (sensitivity, 0.91; specificity, 0.56).[14] The models presented here had thresholds of presence at kappa values ranging from 0.19 to 0.42, the sensitivity ranged from 0.32 to 0.54, and the specificity was higher than 0.90 for all models.

Our models and those published by other authors indicate that our ability to predict triatominae infestation at the household level is moderate with our current methods. In our case, including village as a random effect and the presence of signs of infestation as a fixed effect contributed to obtaining higher positive predictive values (percentage of positive predictions that were truly positive). It is important to remember that

Table 5

ORs for the house factors included in the multivariate generalized logistic models, weighted ORs of factors obtained by modeling averaging (multimodel inference approach), and their relative importance (RI). The direction of the effect of ORs by either increasing (dark gray) or decreasing (light gray) the likelihood of infestation is shown

	Model 1 OR	Model 2 OR	Model 3 OR	Model 4 OR	Model 3 multi model OR	Model 3 multi model RI	Model 4 multi model OR	Model 4 multi model RI
(Intercept)	0.0	0.0	0.0	0.0	0.0	1.00	0.0	1.00
House wall material (adobe/bricks–block–others)	3.03	2.12	1.75	1.57	1.66	0.71	1.87	0.97
House wall material (bajareque–palopique/bricks–block–others)	3.15	3.13	2.35	2.41	1.96	0.71	2.64	0.97
Bedroom wall plastering (deteriorated/not deteriorated)	1.91	1.34	2.12	1.43	1.83	0.95	1.00	0.02
House wall plastering (deteriorated/not deteriorated)	0.64	0.68	0.64	0.67	1.00	0.01	1.00	0.01
Education level (secondary/primary)	1.37	1.27	1.38	1.31	1.00	0.01	1.00	0.01
Education level (high school to college/primary)	0.67	0.76	0.72	0.84	1.00	0.01	1.00	0.01
Education level (none/primary)	1.46	1.63	1.39	1.58	1.00	0.01	1.01	0.01
Land for agriculture (other/yes owner)	0.79	0.79	0.90	0.86	1.00	0.01	1.00	0.01
Land for agriculture (other/yes renter)	0.86	0.92	0.70	0.80	1.00	0.01	1.00	0.01
Land for agriculture (other/no land)	1.96	3.43	2.60	3.91	1.01	0.01	1.01	0.01
Number of dogs (0/>2)	1.02	1.03	1.18	1.16	1.00	0.00	1.00	0.00
Number of dogs (1/> 2)	1.09	1.01	1.21	1.05	1.00	0.00	1.00	0.00
Number of dogs (2/> 2)	0.97	1.08	1.13	1.17	1.00	0.00	1.00	0.00
Number of chickens (0/> = 20)	0.66	0.69	0.61	0.63	0.99	0.02	0.75	0.41
Number of chickens (1–9/> = 20)	0.83	0.97	0.81	0.93	0.99	0.02	0.93	0.41
Number of chickens (10–19/> = 20)	0.96	1.32	0.98	1.30	1.00	0.02	1.08	0.41
Number of cats (0/> = 1)	0.77	0.77	0.80	0.78	1.00	0.02	0.85	0.52
Number of cats (1/> = 1)	1.08	1.14	1.07	1.13	1.00	0.02	1.04	0.52
Number of pigs (0/> = 1)	1.95	1.88	1.32	1.38	1.00	0.01	1.01	0.02
Bed hygiene (bad/good)	1.35	1.33	1.31	1.31	1.01	0.04	1.30	0.84
House hygiene (bad/good)	0.97	1.01	0.94	1.04	1.00	0.01	1.01	0.07
Grain storage in house (no/yes)	0.88	0.87	1.02	0.92	1.00	0.03	0.99	0.04
Firewood piles location (inside-adjacent/no firewood)	0.79	0.93	0.75	0.91	1.00	0.01	1.00	0.01
Firewood piles location (outside/no firewood)	1.25	1.28	1.15	1.19	1.00	0.01	1.00	0.01
Construction materials piles (wood-ceramic tile/no materials)	1.00	0.89	0.92	0.82	1.00	0.01	1.00	0.02
Construction materials piles (wood-clay tile/no materials)	1.32	1.12	1.22	1.10	1.00	0.01	1.00	0.02
Chicken coop location (inside/no coop)	1.54	1.42	1.35	1.31	1.37	0.83	1.00	0.00
Chicken coop location (outside/no coop)	1.55	1.61	1.20	1.25	1.28	0.83	1.00	0.00
Kitchen location (inside/shared)	1.66	1.60	1.86	1.65	1.29	0.53	1.01	0.03
Kitchen location (outside/shared)	1.21	1.57	0.98	1.28	0.89	0.53	1.00	0.03
Floor type (dirt/no dirt)	1.50	1.56	1.36	1.48	1.08	0.21	1.43	0.79
Cluttering (no/yes)	1.45	1.15	1.31	1.15	1.00	0.01	1.00	0.01
Dark room (no/yes)	0.65	0.79	0.61	0.75	0.62	0.90	0.92	0.25
House age (2–6 years/< = year)	1.38	1.38	1.68	1.62	1.40	0.66	1.46	0.80
House age (> = 7 years/< = year)	1.76	1.69	2.39	2.09	1.68	0.66	1.76	0.80
Roof type (metal-cement/tile-vegetable-others)	0.66	0.77	0.84	0.86	1.00	0.02	1.00	0.02
Signs of bug infestation (yes/no)	–	9.85	–	8.72	–	–	9.03	1.00
Window in bedroom (no/yes)	1.14	0.98	1.14	1.08	1.00	0.02	1.00	0.01
Some animal signs/no signs	2.10	1.55	2.22	1.65	1.68	0.67	1.00	0.00
Intermediate animals signs/no signs	1.66	1.43	1.68	1.42	1.52	0.67	1.00	0.00
Multiple animals signs/no signs	2.14	1.37	1.97	1.30	1.70	0.67	1.00	0.00
Random effect variance, standard deviation	No random	No random	0.6, 0.8	1.0, 1.0	–	–	–	–

OR = odds ratio.

model performance could be affected by false negatives, which are not uncommon during traditional man-hour surveys. The efficacy of the man-hour method is low,[41] thus, a house that was not detected as infested in the field could actually be infested. Repeated sampling and new modeling methodologies are now being proposed in cases when detection is not perfect;[42] however, repeated sampling could be difficult when hundreds or thousands of houses are being surveyed.

It is well known that rural houses made of rustic materials can offer countless hiding places for triatomine insects; increased availability of hiding places is positively associated with triatomine population size. A field study conducted in a rural house in Brazil showed that plastering all the walls of a house eliminating cracks and crevices prevented *Triatoma infestans* infestation for around 6 months.[20] A small experiment conducted in Guatemala supported that wall materials could affect triatomine survival: third stage nymphs survived an average of 75 days in plain bajareque, whereas nymphs in plastered and/or painted bajareque survived 60 days or less.[43] A controlled experiment carried out in huts infested with *Triatoma infestans* demonstrated that the number and quality of hiding places had a direct effect on population size and female fecundity. The huts with a higher number of hiding places produced the largest and most fecund populations.[44] A recent field study determined that availability of refuges for insects was positively associated with *Triatoma infestans* infestation and abundance; refuge availability was measured by experienced insect collectors through visual inspection on a scale from 1 (no refuge at all) to 5 (abundant refuges).[45]

House improvement has always been considered an important strategy for the control of triatomines. Carlos Chagas himself focused on improving the houses of the poor at a time when there were no effective insecticides against triatomines, but he soon encountered low political support.[7] Although house improvement is costly and difficult to implement on a large scale, it has been tested as a control strategy in multiple countries. A study conducted in Paraguay found a reduction from 48.6% to 16.4% in *Triatoma infestans* domestic infestation over a period of 18 months in a village where insecticide spraying and improvements in selected houses were used in combination.[22] In Jutiapa, Guatemala, a combination of spraying and house improvements reduced domestic infestation from 5.2% to 1.6% in two villages during a 2-year period.[24] Other experiences in Venezuela and El Salvador have shown that house improvement, which has been achieved by very different routes in these two countries (public policy in Venezuela, and monetary influx as a result of migration to the United States due to the civil war in El Salvador), has significantly reduced triatominae infestation.[8] In the case of El Salvador, house improvements have eliminated infestation by *Rhodnius prolixus*.[8]

It is important to continue efforts to promote house improvement for the long-term sustainability of triatomine control. We believe it is important to highlight that all the combined evidence support this recommendation.[30] Despite great progress in Chagas disease control, a complete eradication of the disease (null parasite transmission in the absence of control or surveillance) might not be feasible in some regions of Latin America.[46] Each region will face different ecological (multiple vectors, non-colonizing vectors, insecticide resistance, etc.) and political difficulties (decentralization of programs and lack of political support). Regardless of the region, house improvement is a key element for the long-term sustainability of the control of triatomines and a strategy to improve the quality of life of the population in rural areas.[8,10,46] An emphasis on house improvement as opposed to eliminating triatomines may also offer a greater opportunity to engage the population in Chagas disease control.[10] House improvement might be more appealing than other methods such as insecticide paints, which received low acceptance in communities in Honduras because of smells and secondary effects,[47] or bed nets, which were accepted by a population in Colombia but still require the introduction of foreign objects or practices.[48] House improvements should be complimented with peridomestic reservoir reduction because peridomestic triatominae foci can persist after house improvement.[24] A recent study in Guatemala showed good community acceptance of rodent control as part of an integrated vector management strategy.[49]

The people in these rural areas already improve their houses on a regular basis. About a quarter of our study population in the three countries reported having made improvements to their homes in the 2 years prior to the study. In Jutiapa, Guatemala, ~50% of the households reported wall improvements.[24] The academic community could contribute improved low-cost house technologies that could help the population protect their houses from triatominae infestation such as a low-cost and long-lasting wall plastering formulation made with local materials.[24] Because household conditions and sanitation are determinants of other diseases and conditions,[50] the health and economic co-benefits of house improvement could be potentially large. The health sector should search for alliances with housing authorities and other sectors (such as the Ministries of Economy, Education, and Agriculture) to achieve the public policies that would be necessary to reduce poor housing.

Our study had several limitations, especially the low frequency of some of the factors evaluated. Very few houses in the villages visited in Guatemala and Honduras were made of block or brick with cement floors; these types of houses were more frequent in El Salvador. The infestation levels in El Salvador and Honduras were low. A larger sample from these two countries would have been ideal to prevent any bias of the results. Surveys were conducted by different teams in different countries during a single season. Ecological factors including altitude, vegetation, and climate were not considered in the models. The models did not incorporate interaction terms. However, we believe that an a priori selection of our hypothesis (set of variables) is a better approach to prioritize factors than algorithm-based selection of variables. Multimodel inference is a modeling methodology that acknowledges that there is not a single "best" model and allows the weighting of factors relative to their contribution to explain the observed variation in the response. This modeling technique is now the preferred method in ecological modeling for triatominae infestation.[11,12,45]

We conclude that in this region, the rural housing factors included in our hypothesis can help predict houses with live infestation and some variables will have more important contributions to the predictions. Including spatial variability and signs of infestation improved the predictions. Results support that rustic conditions in houses are the most important factors in perpetuating *Triatoma dimidiata* infestations. It is thus necessary to continue promoting house improvement as a component of the strategies against Chagas disease vectors and the housing factors studied here can be used to prioritize house improvement.

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