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Community-based surveillance and control of chagas disease vectors in remote rural areas of the Argentine Chaco: A five-year follow-up

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ABSTRACT

Prevention of Chagas disease vector-borne transmission mostly relies on the residual application of pyrethroid insecticide. Persistent or recurrent house infestation after insecticide spraying remains a serious challenge in remote, resource-poor rural areas where public health services face substantial constraints. Here we use generalized estimating equations and multimodel inference to model the fine-scale, time-lagged effects of a community-based vector surveillance-and-response strategy on house infestation and abundance of *Triatoma infestans* in four rural communities of the Argentine Chaco over a five-year period. Householders and community leaders were trained to detect triatomines and spray with insecticides their premises if infested. House infestation and vector abundance were consistently higher in peridomestic habitats than in human habitations (domiciles). Householders supplemented with sensor boxes detected infested domiciles (67%) more frequently than timed-manual searches (49%). Of all houses ever found to be infested by timed-manual searches, 76% were sprayed within six months upon detection. Domestic triatomine abundance was significantly related to house-level insecticide spraying during the previous year (inversely) and current peridomestic abundance (positively). Peridomestic triatomine abundance significantly increased with current domestic bug abundance and maximum peridomestic abundance during the previous year, and was unaffected by insecticide spraying. Our study provides new empirical evidence of the interconnection and flow between domestic and peridomestic populations of *T. infestans* under recurrent insecticide treatments, and supports targeting both habitats with appropriate tactics for longer-lasting, improved vector control. Community-directed efforts succeeded in controlling domestic infestations and interrupting domestic transmission, whereas persistent peridomestic infestations demand sustained control efforts to address domestic reinvasions.

1. Introduction

Chagas disease, caused by *Trypanosoma cruzi* Chagas (Kinetoplastida: *Trypanosomatidae*), is an important vector-borne neglected tropical disease in the Americas, and an emerging disease in non-endemic countries (Bonney, 2014). In the absence of an effective treatment of chronic human infections and vaccines, the prevention of vector-borne transmission typically relies on suppressing house infestations with triatomine bugs. *Triatoma infestans* (Klug) (Hemiptera: Reduviidae), the main vector species in the southern cone countries of South America, has been a target for elimination under the intergovernmental regional initiative for Chagas disease control operating since 1991 (WHO, 2002).

The remarkable adaptation of *T. infestans* to human sleeping quarters (domiciles), feeding frequently from humans and domestic animals, contribute to its prime role as a disease vector (Cohen et al., 2017; Gürtler et al., 2014a). Peridomestic structures housing domestic animals are particularly relevant in the Argentine Chaco eco-region due to their role as sources of *T. infestans* (Cecere et al., 2002, 2004, 2013; Gorla et al., 2009; Gurevitz et al., 2013; Gürtler et al., 2004, 2014b; Hernández et al., 2013); they increase the risk of domestic reinfestation after insecticide applications and thus contribute to the resurgence of *T.*

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cruzi transmission to humans (Gürtler et al., 2007). The key role of peridomestic habitats has been verified for various triatomine species and landscapes (Diotaiuti et al., 2000; Ramsey et al., 2003). In consequence, sustainable Chagas disease vector control crucially depends on thorough residual insecticide applications coupled with continued monitoring of house infestation, and prompt insecticide re-application where needed (Gürtler et al., 2007; Vazquez-Prokopec et al., 2009). Housing improvement may contribute to improved vector control but so far and with very few exceptions, it has been divorced from vector control programs so far (WHO, 2002).

The decentralization of public health services in Latin America since the early 1980s imposed new constraints to the vertical structure of national vector control programs of Chagas disease (Yadón et al., 2006). Lack of adequate, infrastructure, human resources and funding at state levels curtailed vector control operations in many countries (Segura, 2002; Vazquez-Prokopec et al., 2009; Yadón et al., 2006). To respond to these constraints, Argentina developed and implemented a community-based vector surveillance-and-response strategy that included the primary healthcare system (where it existed), and trained community leaders and rural villagers in the use of low-cost sensing devices for detecting triatomines and hand-compression sprayers to apply pyrethroid insecticides (Segura, 2002). This large-scale horizontal program (denominated "Plan Dr Ramón Carrillo") largely reduced the apparent incidence of human infection with *T. cruzi* and house infestation indices over a five-year period, but was deactivated in the context of an unfolding economic crisis and associated political turmoil combined with an intense competition between Chagas and dengue vector control for the scant resources allocated (Segura, 2002; Spillmann et al., 2013; Vazquez-Prokopec et al., 2009).

How to cope with the issue of persisting or recurrent community or house infestation with *T. infestans* in remote rural areas where state-run health services face notorious constraints still is an unresolved challenge (e.g., Gürtler et al., 2007; Segura, 2002). Community engagement has been recognized as a social value in itself, and is an essential component of primary healthcare attention (Espino et al., 2004). Active community participation is one of the most appealing alternatives and a key priority action to achieve effective, locally adapted, and sustainable control of vector-borne diseases (Espino et al., 2004; Rifkin, 2009; WHO, 2017; De Fuentes-Vicente et al., 2018). More specifically, "community participation should become a strategic component of Chagas disease vector surveillance" (Abad-Franch et al., 2011). Moreover, horizontal vector surveillance-and-control preceded by a vertical attack phase was predicted to be the most cost-effective strategy for long-term control of T. infestans and halting the incidence of Chagas acute cases in a hyper-endemic rural district of the Argentine Chaco (Vazquez-Prokopec et al., 2009, 2012). A detailed analysis of house infestation dynamics in the context of community-directed insecticide spraying scheme promoted by the horizontal program was not conducted, nor were householders' responses and the effectiveness of control actions quantified.

To address this knowledge gap, we designed and implemented a participatory health intervention based on training local householders in vector surveillance and insecticide spraying techniques in four rural villages of the Argentine Chaco, and promoted their involvement in housing improvement, monitoring of house infestation and insecticide spraying when needed (Cecere et al., 1999, 2002). The community-wide aggregated effects of these actions lead to the interruption of parasite transmission at the village scale level (Cardinal et al., 2006; Gürtler et al., 2007). Here we use generalized estimating equations (GEE) to model the fine-scale effects of the interventions on the temporal dynamics of house infestation with *T. infestans* in domestic and peridomestic habitats over a five-year period. We also assessed householders' responses to the proposed scheme; the time gap between triatomine detection and subsequent insecticide spraying, and the relative sensitivity of detection methods in domiciles. Our a priori hypotheses were that house spraying by local dwellers would be more effective on domestic triatomine populations than in various peridomestic structures where pyrethroids have a much shorter residual activity and diminished effectiveness (Cecere et al., 2013; Diotaiuti and Texeira-Pinto, 1991; Ferro et al., 1995; Gürtler et al., 2004; Lhoste, 1982; Rojas de Arias et al., 2003); householders' bug collections would be more sensitive than timed-manual collections, as suggested by preliminary findings during the first years of the intervention program (Gürtler et al., 1999), and peridomestic infestations would increase the risk of domestic infestation (Cecere et al., 2002, 2004). This study provides new evidence on the connectedness between peridomestic and domestic triatomine populations in the context of insecticide treatment, and provides a quantitative estimate of the effectiveness of community-based vector surveillance-and-control in a high-risk rural area of the Argentine Chaco. These results are also relevant elsewhere in Latin America, where the resources invested in vector control services have dwindled or are diverted to halt the regional expansion of dengue and other viral diseases transmitted by mosquitoes.

2. Methods

2.1. Study area

Fieldwork was carried out in the neighboring rural villages of Amamá, Trinidad, Mercedes and Pampa Pozo (27° 13´ S, 63° 01´ W), Moreno department, in the Province of Santiago del Estero, Argentina. This set of villages will be referred to as Amamá villages and encompassed 117 houses over the study period specifically covered in this paper. A map illustrating the study area appears in Cohen et al. (2017). The area and history of house infestation with *T. infestans* have been described elsewhere (Gürtler et al., 2007). A house compound encompassed human sleeping quarters (domicile, typically made of adobe walls and a thatched roof) and associated peridomestic structures (i.e., peridomicile), consisting of a patio and 3–8 structures separated from human habitations. Poultry, pigs and goats were raised by villagers for subsistence.

2.2. Study design

All participants were explained the study objectives and signed an informed consent form. The Ethical Review Committee of the National Chagas Institute Dr. Mario Fatala Chaben of the Argentine Ministry of Health and Social Welfare reviewed and approved the study.

As part of a long-term prospective study, a community-wide campaign of house spraying with suspension concentrate deltamethrin (25 mg a.i./m^2) (K-Othrina, Agrevo, San Isidro, Argentina) was carried out by professional spray teams from the National Chagas Service in October 1992, here taken as baseline or 0 year postintervention (YPI) (Cecere et al., 2002). We provide the timeline of the major events in years postintervention (YPI) and also express the exact date of surveys in months postintervention (MPI) for improved precision; exact survey dates are provided in S1 Appendix. In the early surveillance phase, vector control personnel sprayed with deltamethrin only sites infested with *T. infestans* over 1–3 YPI, and the entire house compound over 4 YPI.

A strong community participation component was implemented over 4–9 YPI. The main participatory activities developed by householders and community leaders consisted in detecting house infestation and selectively spraying with insecticide those houses where at least one *T. infestans* was captured or reported by householders, but not when any *Triatoma guasayana* or *Triatoma garciabesi* was caught and when a newly-built house appeared.

Vector surveillance activities were transferred from the research team and vector control personnel to the local communities through three four-hour workshops conducted at the schools of Amamá and Mercedes over 3–4 YPI as described elsewhere (Cecere et al., 1999). Local residents were briefed on the main results of the research project, and trained in how to assemble and inspect sensing devices (see below) used for detecting triatomines in domiciles, catch and store triatomines in a self-sealing plastic bag, and spray house premises with insecticide. Ninety families, 47 from Amamá and 43 from the other villages, were present in at least one of the workshops. Each community elected a member who would receive householders' notifications of a *T. infestans* catch, store the insecticide and hand-compression sprayer, keep records of triatomine notifications and house treatments, and assist families in spraying their house compounds. Three men were selected as leaders: the primary health agent from Amamá, a government employee from Mercedes, and one from Trinidad-Pampa Pozo without a permanent job, who played his role shifting with another person.

House reinfestation was evaluated by several detection methods described elsewhere (Gürtler et al., 1999): i) timed-manual collections (TMC) using 0.2% tetramethrin (ICONA, Argentina) as a dislodjant agent, in which one skilled bug collector searched human sleeping quarters while another searched peridomestic sites for 30 min per site (1 person-h and 0.5 person-h, respectively) at 37, 49, 61, 74, 79, 89 and 120 MPI. Additional searches for triatomines were carried out in peridomestic sites (0.5 person-h per house) at 31, 43, 55, 67, 79, 89 and 120 MPI; ii) householders' bug collections (HD), starting at 7 MPI, when a labeled self-sealing plastic bag was provided to each household to store any triatomine they may catch, and iii) domestic sensor boxes (SB) (Biosensor, Biocientífica de Avanzada^{R}, Buenos Aires) placed on bedroom walls at baseline and replaced as needed. All bugs were identified to species and stage at the field laboratory as described elsewhere (Canale et al., 2000).

2.3. Data management and statistical analysis

We restricted the analysis to a total of 117 house compounds (including 65 from Amamá, 22 from Trinidad, 23 from Mercedes and 7 from Pampa Pozo) with complete data over 4–8 YPI in order to have a homogenous set of records with less chances of any bias, and excluded houses with missing data in most of the eight surveys conducted over that period. The selected study houses were evaluated simultaneously by TMC, HD and SB over the period spanning from 4 to 8 YPI at 49, 61, 74 and 89 MPI, and also by TMC (only in peridomiciles), SB (only in domiciles) and HD (both locations) at 43, 55, 67, and 79 MPI. All surveys were equally spaced temporally except the last one (from 7 to 8 YPI). Missing data for peridomestic infestation and bug abundance at a given survey was taken as zero when the peridomicile had been negative by TMC at the previous survey and remained negative on the subsequent survey, or when the house had not existed before or ceased to exist after the survey. A total of 22 house compounds (6 from Amamá, 7 from Trinidad, 6 from Mercedes and 3 from Pampa Pozo) that did not comply with the above criteria over 4–8 YPI were excluded from the analysis. For each house we also included its status of infestation by late 3 YPI as determined by TMC. All houses, domiciles or peridomiciles positive by TMC after insecticide spraying were taken to be reinfested, regardless of whether the collected bugs may have survived the previous treatment (i.e., not exactly a new infestation) or inmigrated from elsewhere (Schofield, 2001).

The relation between the relative abundance of *T. infestans* (total number of bugs collected by TMC) in domiciles and time-dependent factors, including repeated measurements over the same units, was analyzed by generalized estimating equations models (GEEM) (Ballinger, 2004; Zeger et al., 1988). The same analysis was undertaken for peridomestic triatomine abundance. GEEM were selected because they produce unbiased regression estimates in repeated-measures study designs with non-normal response variables. This statistical approach was also used to analyze the effect of selective insecticide spraying on non-target triatomine species (Rodríguez-Planes et al., 2016). The response (dependent) variables, consisting of count data described by a Poisson distribution, were the number of *T. infestans* caught by TMC in domiciles at time t (*NdomiT*) and in peridomiciles at time t (*NperiT)* of the same 117 house compounds surveyed over four occasions during the spring-summer seasons (late 4 YPI up to early 8 YPI). Consecutive vector surveys conducted 6 and 12 months before the survey conducted at time t were taken to occur at t-1 and t-2, respectively. Similarly, insecticide sprays that had been conducted over the previous 0–5 months- and overthe previous 6 to 12-month period occurred at t-1 and t-2, respectively. The explanatory variables included the current number of bugs in domiciles at time t (*NdomiT*) and at the previous annual survey (*NdomiT-2*); the current numbers of bugs in peridomiciles at time t (*NperiT*), t-1 (*NperiT-1*), and t-2 (*NperiT-2*); the maximum number of bugs captured by TMC in peridomiciles over the two previous surveys (*NperiMax*), and the occurrence of at least one insecticide treatment over the previous year (*Roc12*, a binary variable whose reference level corresponds to the occurrence of an insecticide spray).

Each of the seven regression models for *NdomiT* and for *NperiT* included at least three of the six explanatory variables and any relevant double interaction. The seven regression models analyzed for *NdomiT* were:

1) ˜ NdomiT-2 + NperiT + Roc12;
2) ˜ NdomiT-2 + NperiT-1 + Roc12;
3) ˜ NdomiT-2 + NperiT-2 + Roc12;
4) ˜ NdomiT-2 + NperiMax + Roc12;
5) ˜ NdomiT-2 + NperiT + NperiMax + Roc12;
6) ˜NperiT + NperiT-1 + NperiT-2 + Roc12;
7) ˜ NdomiT-2 + NperiT + NperiT-1 + NperiT-2.

The seven regression models for *NperiT* were:

1) ˜NdomiT + NdomiT-2 + Roc12;
2) ˜NdomiT + NdomiT-2 + NperiT-1 + Roc12;
3) ˜NdomiT + NdomiT-2 + NperiMax + Roc12;
4) ˜NdomiT + NperiMax + Roc12;
5) ˜NdomiT + NperiMax;
6) ˜NdomiT + NperiMax + Roc12 + Roc12*NdomiT;
7) ˜NdomiT + NperiMax + Roc12 + Roc12*NperiMax.

Three regression models for vector abundance in domiciles including an interaction term and one model for vector abundance in peridomiciles did not get to converge (S2 Appendix). The models were implemented using R 3.1.0 (R Core Team, 2014), the geepack package and geeglm function (Højsgaard et al., 2006; Yan, 2002; Yan and Fine, 2004), MuMIn package for multimodel inference, and model.sel and model.avg functions (Burnham and Anderson, 2002). More details of the models appear in S3 Appendix. Domestic and peridomestic bug abundance (median and quartiles) for each survey date and 95% confidence intervals (CI) of proportions were estimated and plotted using R 3.1.0.

Other tests were conducted in Stata 15.1 (Stata Corp, 2017). The Mantel-Haenszel test was used to analyze the risk of having a future infestation (at time t) in domiciles or peridomiciles when the house had been sprayed with insecticide over the previous year (i.e., over the previous two surveys). The relative sensitivity of HD over 1996–2000 was calculated by considering the number of houses with infested domiciles detected by HD (regardless of whether they were found positive by any other method) relative to the total number of houses with infested domiciles as determined by any method (SB, HD and TMC). We used a similar procedure to compute the relative sensitivities of TMC and of HD pooled with SB. For SB, domiciles were taken as infested if any nymphal instar or adult of *T. infestans* (not eggs, fecal smears or exuviae) was found inside or against an outside wall. The significance of the observed differences between pairs of detection methods of domestic infestations (i.e., HD supplemented with SB (HD/SB) versus TMC) was evaluated using the McNemar's χ^2 test with one degree of freedom.

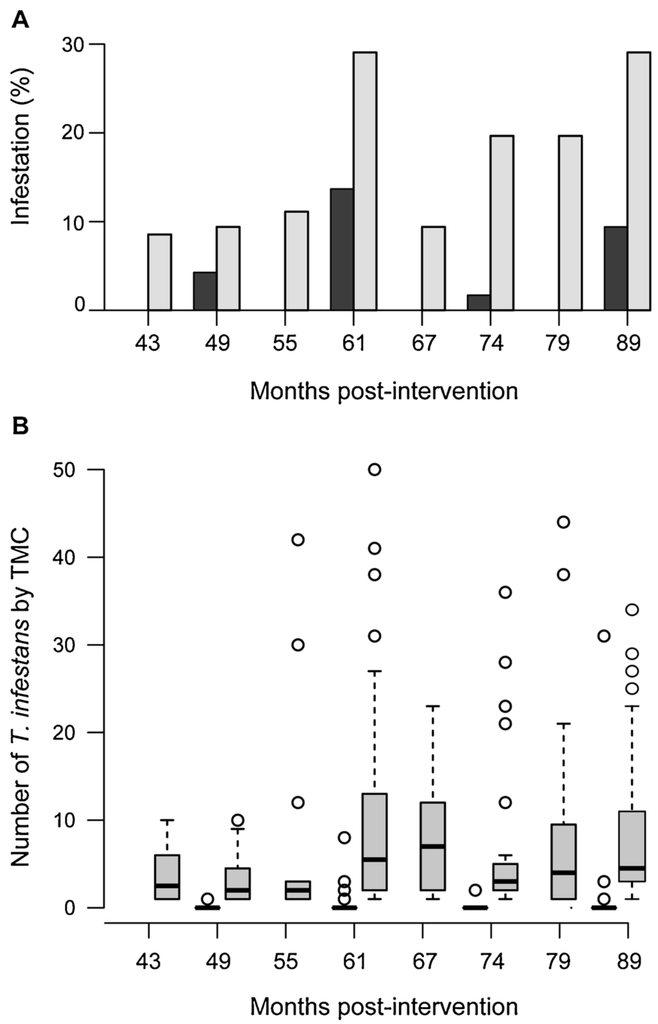

Fig. 1. House infestation (a) and relative abundance of *T. infestans* (b) in domiciles (black) and peridomiciles (light grey) from 43 to 89 MPI in Amamá villages under community-based vector surveillance. Horizontal lines indicate median bug abundance by TMC, whiskers represent 1.5 times the interquartile range (box), and open circles are outliers.

3. Results

The prevalence of house infestation with *T. infestans*, as determined by TMC, varied from 12.8% to 38.5% over the five-year period. Peridomestic infestation (range, 8.5–29.1%) and median bug abundance (range, 2–7 triatomines per unit effort) consistently exceeded the values recorded in domiciles (1.7–13.7% and 1–3 bugs, respectively) (Fig. 1). Peridomestic infestation tended to peak in late spring or summer surveys of 5–8 YPI but vector abundance did not exactly match that pattern. The prevalence of house infestation in domiciles (13.7% and 9.4%) and peridomiciles (29.1%) peaked simultaneously over the hot seasons of 5 and 8 YPI (Fig. 1a). In contrast, the relative abundance of *T. infestans* in domiciles remained low throughout (Fig. 1b).

Householders carried out a total of 126 insecticidal sprays at 85 houses over 4–8 YPI. The biannual rate of house spraying with insecticides rose to a peak of 35.0% between 61 and 67 MPI (Fig. 2), matching the infestation peak detected in domiciles (13.7%) and peridomiciles (29.1%) (Fig. 1a). Spray rates ranged from 3.5% to 17.1% at other times. The sprayed houses received one (63.5%, 54 houses), two (24.7%, 21), and three treatments (11.8%, 10). Most treatments (73%) covered domestic and peridomestic habitats of each house; 20.6% only included domestic habitats, and 6.3% only peridomestic ones.

Residual insecticide spraying applied by householders during the preceding year significantly reduced the relative odds of occurrence of *T. infestans* at time t (as determined by TMC) stratified by type of habitat (i.e., domicile versus peridomicile) (Table 1; Mantel-Haenszel test, $\chi^2 = 5.60$; df = 1, $P = 0.018$; odds ratio, OR = 0.56, 95% confidence interval, CI = 0.35–0.91). The relative odds of infestation after spraying significantly decreased in domiciles (OR = 0.16, 95% confidence interval, CI = 0.02–0.64), and tended to decrease in peridomiciles (OR = 0.76, 95% CI = 0.43–1.30) although not significantly so.

Tables 2 and 3 show model selection indices and regression coefficients for selected GEE models of the relative abundance of *T. infestans* (as determined by TMC) in domiciles and peridomiciles. The domestic abundance of *T. infestans* was best described by the model that included the local occurrence of an insecticidal spray over the previous year ($P < 0.001$), which reduced subsequent domestic triatomine abundance, and peridomestic triatomine abundance, which was directly associated with domestic abundance at the current survey ($P = 0.043$). Table S1 shows regression coefficients and other statistics for the averaged model. In peridomestic habitats, the full model that best described variations in the relative abundance of *T. infestans* included three explanatory variables and one interaction term; only current domestic triatomine abundance at t ($P < 0.001$) and maximum peridomestic triatomine abundance over the previous year ($P = 0.002$) exerted statistically significant effects, not insecticide spraying (Table S2).

Nearly half (49%) of all houses infested with *T. infestans* by TMC were sprayed with insecticides during the year that followed triatomine

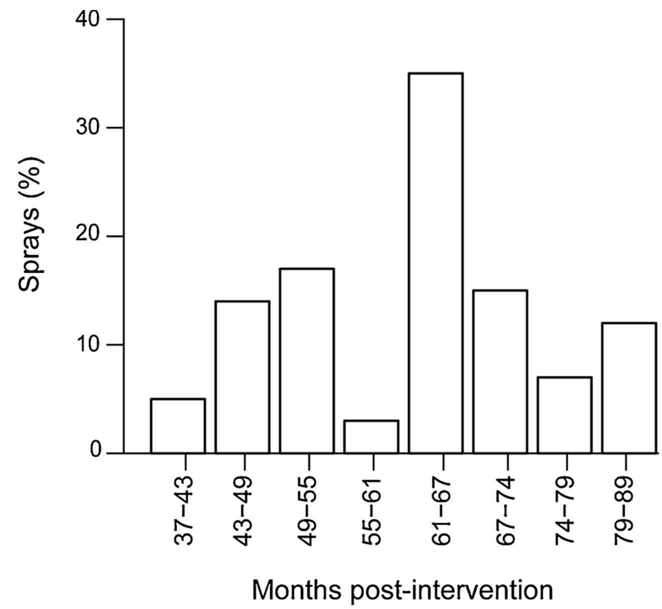

Fig. 2. Percentage of houses sprayed with insecticides by householders from 37 to 89 MPI in Amamá villages.

Table 1
Relationship between house spraying with insecticide applied by householders during the preceding year and subsequent house infestation with *T. infestans* at time t (as determined by TMC) according to type of habitat (domicile and peridomicile) in Amamá villages over a four-year period (4–8 YPI).

Insecticide spraying over the previous year (t_1-t_2)	Type of Habitat	Subsequent infestation at t (No. of houses inspected)		% infested
		Yes	No	
Yes	Domicile	2	122	1.6
	Peridomicile	23	101	18.5
No	Domicile	32	312	9.0
	Peridomicile	79	265	23.0

Table 2
Model selection indices and regression coefficients for the relative abundance of *T. infestans* in domiciles at time t (as determined by TMC) in Amamá villages. Includes models with weights greater than 0.

Model	Intercept	Ndomi T-2[a]	Nperi T[b]	Roc12[c]	Nperi Max[d]	Nperi T-1[e]	Nperi T-2[f]	QIC	Delta QIC	Weight QIC
6	−1.21		0.051	−2.69	−245	0.025	−0.040	498	0	0.791
1	−1.22	−0.084	0.056	−2.79	−247			503	4.56	0.081
5	−1.22	−0.131	0.054	−2.79	−247		0.002	504	5.65	0.047

[a] NdomiT-2 is the number of domestic bugs determined by TMC at the previous annual survey.
[b] NperiT is the current number of peridomestic bugs determined by TMC at time t.
[c] Roc12 is the occurrence of at least one insecticide treatment over the previous year.
[d] NperiMax is the maximum number of bugs captured in peridomiciles over the previous year (i.e., two surveys).
[e] NperiT-1 is the number of peridomestic bugs determined by TMC 6 months before t.
[f] NperiT-2 is the number of peridomestic bugs determined by TMC at the previous annual survey.

detection (Table 4). House spray rates were more frequent over 5–6 YPI (64–72%) than over 7–9 YPI (25–35%), which coincides with more frequent spraying of infested domiciles (80–94%) than of infested peridomiciles (60–64%) over the first period. On average, 76% of all houses ever found to be infested by TMC were sprayed within the first six months upon bug detection over 4–6 YPI (Table 4). Within this group, 89% of the house sprays occurred when *T. infestans* was captured at least in domiciles, and 71% when it was found in peridomiciles only.

The relative sensitivity of vector detection methods in domiciles varied over time (Table 5). On average, more houses with infested domiciles were detected by HD supplemented with SB (HD/SB) (67%, 47 of 70) than by TMC (49%, 34 of 70). Excluding the year 6 YPI (when only two foci were detected), the relative sensitivity of HD/SB ranged from 50% to 86% whereas that of TMC varied from 23% to 61%. HD/SB performed significantly better than TMC at 4 YPI (McNemar´s test, $\chi^2 = 9.80$, df = 1, $P = 0.002$), whereas TMC detected significantly more than SB at 5 (McNemar´s test, $\chi^2 = 4.57$, df = 1, $P = 0.032$) and 8 YPI (McNemar´s test, $\chi^2 = 5.33$, df = 1, $P = 0.021$). The relative sensitivity of HD only or supplemented with SB decreased over time whereas that of TMC tended to increase with increasing triatomine abundance. Only at 4 YPI did the sensitivity of HD (64%) exceed that of TMC (23%) (McNemar´s test, $\chi^2 = 4.76$, df = 1, $P = 0.029$).

Table 4
House spraying with insecticides during the year that followed the detection of *T. infestans* (as determined by TMC) in Amamá villages.

Habitat where *T. infestans* was caught	Years postintervention					
	4	5	6	8	4–6	Overall
Peridomicile only						
No. of total sprays	12	27	9	18	48	66
% sprayed over t, t + 1[a]	67	67	89	–	71	–
% of infested houses sprayed[b]	60	64	27	33	51	44
At least in domicile						
No. of sprays	4	15	0	5	19	24
% sprayed over t, t + 1[a]	100	87	–	–	89	–
% of infested houses sprayed[b]	80	94	0	45	79	69
Overall						
No. of sprays	16	42	9	23	67	90
% sprayed over t, t + 1[a]	75	74	89	–	76	–
% of infested houses sprayed[b]	64	72	25	35	56	49

[a] Includes infested houses sprayed within the first six months after detection of *T. infestans* at t.
[b] Includes infested houses sprayed within one year after detection of *T. infestans* at t.

4. Discussion

Our results show that a community-based vector-surveillance-and-response strategy based on householders' actions with minimal external support held domestic bug infestation and abundance at low levels over a five-year period, mostly < 10% and 50% of domiciles with < 1 bug per unit effort, respectively. This control strategy also included health promotion, periodic supervision and delivery of insecticide in a region where *T. infestans* has not displayed pyrethroid resistance yet, unlike in other locations of the Gran Chaco (Fronza et al., 2016; Picollo, 2001).

Householders perceived domestic infestations and acted on them mostly within six months after vector detection over the first three years of the community-based program (5–7 YPI). The protective effects of household-based insecticide treatments significantly reduced the chances of subsequent infestation in domiciles, more so than in peridomiciles, as predicted. Even if householders' technical procedures and treatment coverage or timing were not perfect, community-directed efforts were successful in controlling domestic infestations since triatomine abundance did not return to preintervention levels, and virtually interrupted the domestic transmission of *T. cruzi* (Cardinal et al., 2006; Gürtler et al., 2007).

Our regression analyses allowing for time-lagged responses suggest that domestic and peridomestic triatomine populations were closely intertwined, as predicted. The longer a peridomestic focus remains infested, the greater the chance of acting as a source and reinfesting its surroundings (Cecere et al., 2004, 2006). The relevance of peridomestic habitats as sources of several triatomine species that invade human sleeping quarters is widespread in South and Central America (e.g., Dumonteil et al., 2004; Grijalva et al., 2011).

Table 3
Model selection indices and regression coefficients of the relative abundance of *T. infestans* in peridomiciles at time t (as determined by TMC) in Amamá villages. Includes models with weights greater than 0.

Model	Intercept	NdomiT[a]	Roc12[b]	NperiMax[c]	NdomiT-2[d]	NperiMax* R12	QIC	Delta QIC	Weight QIC
7	0.365	0.075	−0.322	0.047		−0.064	−65.6	0	0.847
3	0.359	0.073	−0.708	0.059	−0.291		−62.1	3.49	0.148
4	0.348	0.073	−0.777	0.050			−55.3	10.33	0.005

[a] NdomiT is the current number of domestic bugs by TMC at time t.
[b] Roc12 is the occurrence of at least one insecticide treatment over the previous year.
[c] NperiMax is the maximum number of bugs captured in peridomiciles over the previous year.
[d] NdomiT-2 is the number of domestic bugs by TMC at the previous annual survey.

Table 5
Annual domestic infestation with *T. infestans* and relative sensitivity according to detection method and year postintervention in Amamá villages.

	Number of infested domiciles[a]									
	Only by			by HD supplemented with			by SB	Relative sensitivity[b]		
YPI	HD	SB	TMC	SB	TMC	SB and TMC	and TMC	HD	HD/SB	TMC
4	13	4	3	0	0	1	1	64	86	23
5	9	3	9	0	2	1	4	43	68	57
6	0	0	2	0	0	0	0	0	0	100
8	5	2	9	0	1	0	1	33	50	61
Overall	27	9	23	0	3	2	6	46	67	49

[a] The total number of infested domiciles, as determined by any of the three detection methods, was 22, 28, 2, and 18 from 4 to 6 and 8 YPI, respectively.
[b] Relative sensitivity (expressed as a percentage) was calculated as the number of infested domiciles detected by a specific method or combination of methods relative to the total number of infested domiciles detected by any of the three methods (HD, SB, and TMC).

The effectiveness of insecticide spraying conducted by householders was greater in domestic premises than in peridomestic structures. The same result was obtained when houses were treated by professional spray teams over the first years of surveillance and in an insecticide trial in Santiago del Estero (Cecere et al., 2002, 2013), and in a three-year intervention trial conducted in Chaco province (Gurevitz et al., 2013). The limited effects of insecticide-based strategies on peridomestic infestations were also reported for *Triatoma pallidipennis*, *Triatoma barberi* and *Triatoma dimidiata* in Mexico (Dumonteil et al., 2004; Ramsey et al., 2003), and *Rhodnius ecuadoriensis* and *Panstrongylus howardi* in Ecuador (Grijalva et al., 2011). This remarkably consistent pattern among multiple rural areas and triatomine species strongly suggest that the effectiveness of pyrethroids may be intimately related to the type of habitat and substrate than to the species of triatomine involved and other technical procedures. In general, the limited effectiveness of pyrethroids in peridomestic structures is closely related to the prompt loss of its residual effects outdoors (through insolation, rainfall) (Gürtler et al., 2004), the type of substrate, traditionally of mud, thatch or wood (Diotaiuti and Texeira-Pinto, 1991; Ferro et al., 1995), and to the difficulties faced when spraying complex structures with multiple layers and refuges for triatomines (Cecere et al., 2006, 2013).

Our study shows that the annual rate of insecticide spraying declined over time as domestic vector detection by HD decreased and peridomestic infestation increased. Peridomestic foci apparently were not perceived by householders as a potential hazard or nuisance that justified the added labor of spraying several peridomestic structures with insecticide. This behavior may be partially related to our earlier feedback to the study communities, indicating that peridomestic triatomines of any of the local species were rarely infected with *T. cruzi* during the surveillance phase (Cecere et al., 1999). Additionally, householders frequently reported the surrounding dry forest or scrub as the sources from where *T. infestans* and other triatomines invaded domiciles. Whether the sole presence of *T. infestans* in peridomiciles would stimulate householders to spray their premises on a long-term basis is uncertain and remains for future investigation.

The lack of a health education program to increase risk perception and the visibility of Chagas disease may also constitute another barrier to household participation, as identified in the context of an insecticidal campaign in Peru (Paz Soldán et al., 2016). Consistent monitoring of house infestations by health assistants and technicians was found to be significantly related to the responsiveness of health services in settings infested with *T. dimidiata* (Hashimoto et al., 2015). Hence, shortening the interval length between visits by healthcare agents may reinforce community-based surveillance responses in settings with weak health systems. But no working control strategy is bullet-proof: reductions in government-allocated health budgets amid sudden changes in policy and office administration, as a prelude to the 2001–2003 Argentine crisis, notoriously affected the availability of transportation, periodic supervision and delivery of insecticide, until the horizontal program collapsed.

Householders effectively detected the presence of domestic triatomines, more so during the first two years of the community-based program (5–6 YPI) when infestations were more frequent, and then tended to decline over time. The combination of householders' bug collections and sensor boxes outperformed any single method, although HD/SB sometimes failed to detect low-density domestic infestations revealed by TMC despite of its limitations (Abad-Franch et al., 2011). The performance of SB is partially related to its structure, site of placement and duration of exposure; the longer the time bugs spend inside it the greater the chance they leave any sign of infestation such as triatomine fecal smears, exuviae or eggs. In the current study, however, we only considered the presence of *T. infestans* nymphs or adults as evidence of domestic infestation because most of the indirect signs could not be assigned to a given triatomine species, and there were other secondary triatomine species invading house premises. The use of SB and HD demand some basic training of local residents and periodic refreshment workshops, and are suitable for large-scale community-based surveillance of domestic infestations and house invasion by various triatomine species. More sensitive devices for early detection of domestic infestations at low bug densities, such as odor-baited traps (Rojas de Arias et al., 2012), may enhance the effectiveness of control actions if bug detection is coupled with a prompt control response.

Our analyses have some limitations. Houses from all study villages were pooled for analysis in order to increase the sample size, despite house infestation dynamics and householders' responses differed between villages to some extent. The number of villages was too low to include them as a random variable in the analysis, and moreover, insecticide effects are expected to be stronger at the household level than at the community level. Although our analyses are based on the records of insecticide spraying and triatomine detection kept by local community leaders, these reports were checked with householders at each survey. Our GEEM-based analysis assumed equal spacing between occasions, although this was not the case between May 1999 and March 2000. This is not a major concern because GEEM are robust to misspecifications of the initial relationship of the within-subject correlation structure (Liang and Zeger, 1986). Because HD and SB are affected by additional sources of heterogeneity (e.g., householders' commitment, location effects), our measure of the relative abundance of *T. infestans* per site is based on using a roughly similar catch effort per unit of habitat (site) on repeated occasions over time. The relative sensitivity of triatomine detection methods rests on the assumption that the combined results of all methods (HD, SB and TMC) on repeated occasions would detect any established domestic infestation (Gürtler et al., 1999).

4.1. Implications for vector control

Our five-year study at a fine spatial scale provides new evidence on the interconnection of *T. infestans* populations from domestic and peridomestic habitats, mainly at the scale of a house compound (Gürtler et al., 2014b), and supports the hypothesis of intense flow of triatomines between both habitats through active flight or walking dispersal (Vazquez-Prokopec et al., 2006). These results stress the need of considering both types of habitats for longer-lasting, improved vector control, and agree with the notion of fine-scale panmictic units (Brenière et al., 2013).

Community-based vector control is especially appropriate for remote, sparsely populated rural areas in which accessibility and resource constraints (personnel, vehicles and per diems) are structural obstacles. This strategy could include other tactics: application of more appropriate insecticide doses and spray rates for suppressing peridomestic infestations (Cecere et al., 2013); environmental and host management (Gorla et al., 2013); spatial analysis to identify hot spots of (re)infestation for targeted vector control (Cecere et al., 2004; Manne et al., 2012; Vazquez-Prokopec et al., 2009), and use of improved sensing devices apt for community-based vector surveillance (Rojas de Arias et al., 2012). Although residents from rural areas are familiar with commercial pesticides for domestic or agricultural pest control, community-based vector control strategies should assess householders' knowledge on the risks posed by handling insecticides, and provide proper training in their safe usage and application (Rozendaal, 1997). Community participation is "sine qua non" for effective, sustainable vector and disease control, more so in remote, resource-constrained rural areas.

Our intervention sheds light on some of the challenges faced by community-based vector control strategies in sparse rural settings. Data presented here can be successfully analyzed under a One Health approach to build a larger understanding of vector control and surveillance of Chagas disease by thinking the multiple biological, social and environmental interactions as parts of an integrated system (Benelli and Duggan, 2018). Ensuring a sustainable strategy based on rural community participation requires more research on the practical aspects of fostering community participation, government frameworks and scaling of outcomes (Kenny et al., 2015). A better understanding of the factors that enhance and impede community participation is crucial (George et al., 2015). New approaches based on integrated vector management and active surveillance-response (Yoshioka et al., 2017) are essential for the elimination of vector-borne transmission of *T. cruzi* in Latin America by 2020, as proposed by the London's Declaration on Neglected Tropical Diseases (WHO, 2012).

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.actatropica.2018.12.038.

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