Effectiveness of Large-Scale Chagas Disease Vector Control Program in Nicaragua by Residual Insecticide Spraying against *Triatoma dimidiata*

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Abstract. Chagas disease is one of the most serious health problems in Latin America. Because the disease is transmitted mainly by triatomine vectors, a three-phase vector control strategy was used to reduce its vector-borne transmission. In Nicaragua, we implemented an indoor insecticide spraying program in five northern departments to reduce house infestation by *Triatoma dimidiata*. The spraying program was performed in two rounds. After each round, we conducted entomological evaluation to compare the vector infestation level before and after spraying. A total of 66,200 and 44,683 houses were sprayed in the first and second spraying rounds, respectively. The entomological evaluation showed that the proportion of houses infested by *T. dimidiata* was reduced from 17.0% to 3.0% after the first spraying, which was statistically significant ($P < 0.0001$). However, the second spraying round did not demonstrate clear effectiveness. Space-time analysis revealed that reinfestation of *T. dimidiata* is more likely to occur in clusters where the pre-spray infestation level is high. Here we discuss how large-scale insecticide spraying is neither effective nor affordable when *T. dimidiata* is widely distributed at low infestation levels. Further challenges involve research on *T. dimidiata* reinfestation, diversification of vector control strategies, and implementation of sustainable vector surveillance.

INTRODUCTION

Chagas disease is one of the most serious public health problems in Latin American countries. Its etiological agent, *Trypanosoma cruzi*, is mostly transmitted by hematophagous triatomine insects, followed by blood transfusion and oral intake.¹ The estimated prevalence of Chagas disease in 18 Latin American countries has gradually decreased in recent years from 1.448% in 2005 to 1.055% in 2010.^{2,3} The reductions in prevalence are considered to be mainly owing to advances in large-scale vector control and screening of blood transfusions in both South and Central America.⁴

The classical vector control strategy has three phases: 1) preparatory phase for risk mapping and general programming, 2) attack phase for conducting multiple rounds of large-scale insecticide spraying of houses, and 3) surveillance phase for detecting residual foci of triatomine insects after large-scale spraying.⁵ In South America, this vector control strategy has drastically reduced the house infestation level of *Triatoma infestans*, and has consequently led to the interruption of vector-borne transmission of Chagas disease.⁶ After this success in South America, Central American countries also implemented similar vector control programs for eliminating *Rhodnius prolixus* and reducing *Triatoma dimidiata*. Effectiveness of the vector control program was proven in Guatemala with respect to interrupting *T. cruzi* transmission by *R. prolixus*.⁷ Neighboring countries followed the same vector control scheme, and *R. prolixus* is considered to be nearly eliminated in Central America.⁸ Currently, Central American countries are addressing interruption of *T. cruzi* transmission by *T. dimidiata*.⁹

Triatoma dimidiata is considered a species complex. Its level of adaptation to human dwellings seems to vary widely among regions, from non-domiciled populations in the Yucatan Peninsula and Belize to highly domestic populations in Guatemala.¹⁰ In locations where domestic populations of

T. dimidiata are predominant, house infestation by this vector is strongly associated with poor housing conditions and the presence of animals in sleeping areas of the dwelling.¹¹ *Triatoma dimidiata* is susceptible to pyrethroid insecticides. A small-scale field test showed that house infestation by this species could be prevented for 4 months after indoor residual spraying.¹² Large-scale operations in eastern Guatemala also showed that large-scale insecticide spraying was effective in substantially reducing house infestation by *T. dimidiata*.^{13–15} However, unlike *R. prolixus*, eliminating domestic populations of *T. dimidiata* is difficult because of its capacity of reinfesting human dwellings after insecticide spraying. Such reinfestation by *T. dimidiata* is likely to occur with the passage of time after spraying and in geographical hot spots.¹⁶

In Nicaragua, the first national entomological survey was conducted in 1998–1999. Among 15 departments surveyed, *R. prolixus* and *T. dimidiata* were found in 6 and 15 departments, respectively. By department, the house infestation index (number of houses infested/number of houses investigated $\times 100$) of *T. dimidiata* ranged from 0.1% to 10.6%.¹⁷ Based on this first survey, the Nicaraguan Ministry of Health (MoH) began a vector control program, mainly for *R. prolixus*. Despite limited geographic coverage, chemical control was successfully implemented toward elimination of *R. prolixus*.¹⁸ Consequently, the interruption of *T. cruzi* transmission by *R. prolixus* was certified in 2011.¹⁹

Control of *T. dimidiata* began systematically in 2010, when the MoH conducted a baseline entomological survey with technical and financial support from the Japan International Cooperation Agency (JICA) and Pan American Health Organization (PAHO). This survey, in five departments in northern Nicaragua, determined that the house infestation index of *T. dimidiata* at municipality level ranged from 0.4% to 19.1%.²⁰ After this baseline survey, the MoH planned large-scale insecticide spraying to reduce indoor populations of *T. dimidiata*. In this article, we report results of the large-scale spraying program and evaluate its effectiveness in controlling domestic *T. dimidiata* in Nicaragua. Further challenges are also discussed.

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METHODS

Site. The large-scale spraying program was implemented in five departments of northern Nicaragua, namely, Estelí, Jinotega, Madriz, Matagalpa, and Nueva Segovia. In terms of public health administration, these departments cover 49 municipalities in which approximately 3,500 communities are distributed geographically. The total population of the five departments as a whole is 1,700,000, and there are approximately 315,000 dwellings.

Insecticide spraying strategy. The operational goal of the large-scale spraying program was set to reduce the house infestation index of *T. dimidiata* to less than 5%. The transmission risk of *T. cruzi* is considered rare when the house infestation index is below 5%. We applied this same value because although this cutoff value is not based on robust scientific evidence, it has been used conventionally in the control of *T. dimidiata*.²¹

Initially, we selected 24 municipalities to conduct large-scale insecticide spraying, in which the house infestation index of *T. dimidiata* was more than 5% in the baseline entomological survey of 2010.²⁰ After the spraying program was initiated in 2011, we obtained more funding, which enabled us to expand the target areas. By involving municipalities adjacent to those initially selected, the spraying program eventually reached 34 municipalities in total.

The spraying program was carried out in two rounds. For the first round, we prioritized communities with official records of detected *T. dimidiata* during the period 1998–2010. In the selected communities, all existing dwellings were targeted to be sprayed. In urban areas, exceptionally, only houses with known vector infestation were sprayed. At the end of the spraying activities, the sprayers roughly assessed house infestation levels, namely, flushed-out triatomine bugs were searched for 10 minutes after spraying in each sprayed house. When *T. dimidiata* was confirmed in more than 5% of sprayed houses in a community, that community was selected for the second round of spraying. As the first round of spraying, the second round targeted all houses to be sprayed in the selected communities.

The Nicaraguan MoH organized one or two field teams in each target municipality to conduct spraying activities. The field team was composed of one supervisor and five or six sprayers. The supervisors were MoH vector control technicians with 10–30 years' experience working in vector control activities. The sprayers were contracted temporarily and trained in spraying techniques and data collection. In target communities, the supervisor assigned up to six houses per day to each sprayer. The quality of spraying techniques was checked daily by the supervisor on site.

Insecticide and spraying technique. In this spraying program, we used two kinds of pyrethroid-derivative insecticide: etofenprox (20% wettable powder at 0.250 g active ingredient (a.i)/m²) and alpha-cypermethrin (10% wettable powder at 0.030 g a.i/m²). Both are recommended for triatomine control.²² Pyrethroid derivatives have residual vector-controlling effects for several months after application. We principally followed the standardized spraying technique for malaria control, using 8-L Hudson X-pert professional spray tanks (H. D. Hudson Manufacturing Co., Chicago, IL).²³ This standard technique allows sprayers to apply solutions of insecticide diluted in water at a rate of 40 mL/m² on target surfaces.

After explaining the objective of the spraying program to householders, sprayers began the application of insecticide. In intradomestic areas under the house's ceiling, the inner walls, wooden furniture, and wooden beams were sprayed. Bedrooms and sleeping areas were prioritized for spraying because *T. dimidiata* bugs are often found around beds.²⁴ Kitchens were not sprayed, to avoid contamination of stored food or water with insecticide. In particular, larger amounts of insecticide were deposited within cracks in walls, if present, for improved effectiveness against *T. dimidiata* hidden inside the cracks. Insecticide was also sprayed in peridomestic areas, especially if chicken coops or pig pens were present, or any other kind of potential refuge for triatomine bugs such as piles of firewood, bricks, adobe, or tiles in courtyards.

For data collection, sprayers registered the following data in paper format: date of spraying, name of community, geographic coordinates, family name, amount of insecticide used, and number of vectors found. Supervisors checked the data quality and aggregated house-level data into community level. In rural communities where 100% of existing houses were targeted, the spraying coverage (% of existing houses sprayed in a target community) was calculated. Community-level data were sent to MoH departmental health offices and entered into a digital database. Triatomine bugs found by sprayers were also sent to these departmental offices for taxonomical identification. In cases of bug misidentification by sprayers, the information was corrected in the database.

Cost estimation. We collected financial data, to estimate the cost of insecticide spraying. The spraying program was financed by multiple sources including the PAHO and the JICA project, and collateral funding was provided by the Non-Project Grant Aid from the Japanese government. All funds were centrally managed by the Nicaraguan MoH. To estimate the insecticide cost, we used JICA project financial reports, which recorded the price of insecticide in 2010–2013. Combined with the spraying activity database, which provided the average amount of insecticide used per house, we calculated the cost of insecticide per house. For operational costs, including fuel and daily allowance, we used MoH financial records containing the 2012 budgetary disbursements for spraying activities during the first semester of 2013. The operational cost per house was also estimated.

Entomological evaluations. To measure the effectiveness of insecticide spraying, we designed a quasi-experimental pre-post test without a control group. To compare entomological levels before and after spraying, we intentionally targeted communities that had been assessed in the baseline entomological survey of 2010, which were included in each round of spraying. High-risk communities tended to be targeted in the entomological evaluation because we selected communities for the spraying program that had a history of vector infestation and that were within municipalities with higher infestation levels. We evaluated the same houses in these target communities that had been assessed in the 2010 baseline survey. If family members were absent during the entomological evaluation, inspectors repeatedly visited the targeted houses until examination could be completed. Abandoned or demolished houses were not inspected. Under an assumption that the residual effects of insecticide last up to 6 months, we planned to conduct the evaluations between 90 and 180 days after the first and second rounds of spraying.

We used the man-hour search method as an evaluation technique.^{25,26} At each target house, two trained inspectors, who were the MoH vector control technicians, searched for triatomine bugs for 30 minutes using searchlights and tweezers. Captured bugs were sent to the MoH's departmental health offices for taxonomical identification. This method was used in the 2010 baseline survey; therefore, the pre- and post-spraying data are comparable in terms of evaluation technique. Inspectors registered community-level data including number of houses examined, number of houses infested by triatomine bugs, site of bug infestation (intra- or peridomestic), and time lapse between spraying and evaluation.

Statistical analysis. We assessed the effectiveness of insecticide spraying by comparing the entomological data obtained before and after each round of large-scale spraying. Because house-level data were unavailable for this study, we used community as the unit of analysis and calculated the house infestation index (number of houses infested by *T. dimidiata*/number of houses examined) for each community. Using Stata Statistical Software Release 13.1 (StataCorp LP, College Station, TX), we used the Wilcoxon signed-rank test to assess differences in house infestation indices before and after spraying. Pearson's χ^2 test was applied to analyze the relationship between pretreatment house infestation levels and posttreatment reinfestation by *T. dimidiata*. All statistical analyses were conducted with significance level of 5%.

Mapping and space-time analysis. To understand spatial patterns of reinfestation by *T. dimidiata* after insecticide spraying, we created a digital map by plotting those communities in which the two entomological evaluations had been conducted. We collected the geographic coordinates at the approximate center of each community using portable Global

Positioning System (GPS) handsets. Administrative boundary maps were provided by Harvard Dataverse Network (<https://thedata.harvard.edu/dvn/>). Using QGIS version 2.2.0 software, we mapped the communities showing house infestation indices of *T. dimidiata* at the baseline survey and the two entomological evaluations. Communities with unavailable or inaccurate GPS coordinates were excluded from mapping. Then we used SaTScan version 9.4 software to detect clusters of high infestation in a space-time setting by a Bernoulli model.²⁷ This software scans a window across time and space, noting the number of observed and expected observations inside the window at each location. The window with the maximum likelihood is the most likely cluster in which more high-risk sites are found. To adjust the length of time intervals among the baseline survey and two entomological evaluations, we assigned generic time being time 1 for the baseline survey, 2 for the first entomological evaluation, and 3 for the second entomological evaluation.

RESULTS

A timetable of the spraying program is given in Figure 1. During the program period (2010–2014), 34 municipalities were involved, among which 23 completed two rounds of insecticide spraying and entomological evaluation. Because the spraying program was implemented gradually according to the available financial resources, the first round of spraying and entomological evaluation was conducted at different time points among the different municipalities.

Insecticide spraying. Table 1 summarizes the results of the insecticide spraying program by department. Overall, the first spray round was implemented in 34 municipalities and

FIGURE 1. Timetable of large-scale insecticide spraying and entomological evaluation by municipality, 2010–2014. Numbers I–IV represent quarters: I, January–March; II, April–June; III, July–September; and IV, October–December. Letters in the table represent type of activity: S1, first round spraying; S2, second round spraying; E1, first entomological evaluation; and E2, second entomological evaluation. In the municipality of Jinotega, first round spraying was discontinued owing to financial reasons.

TABLE 1
Results of large-scale insecticide spraying programs for controlling triatomine vectors in five departments in Nicaragua, 2010–2014

Department	No. of municipalities targeted	No. of communities in the targeted municipalities	No. of communities selected	No. of houses in the selected communities*	No. of houses sprayed	No. of houses with <i>Triatoma dimidiata</i>	No. of houses with <i>Rhodnius prolixus</i>
First round of spraying							
Estelí	6	590	267	22,639	15,792	1,047	0
Jinotega	4	374	179	21,744	13,539	676	0
Madriz	6	236	100	7,135	6,486	255	0
Matagalpa	8	719	286	35,027	21,549	949	2
Nueva Segovia	10	509	141	9,900	8,835	345	0
Total	34	2,428	973	96,445	66,200	3,272	2
Second round of spraying							
Estelí	6	590	252	16,556	13,695	483	0
Jinotega	4	374	101	9,392	6,082	287	0
Madriz	2	43	26	2,555	2,288	41	0
Matagalpa	7	630	185	19,626	17,410	341	0
Nueva Segovia	9	447	100	6,031	5,208	118	0
Total	28	2,084	664	54,160	44,683	1,270	0

*Sum of all existing houses in urban and rural communities. Note that this sum involves urban houses that were not targeted for spraying.

covered 66,200 houses in 973 communities. Spraying coverage was 85.0% in rural communities. During the spraying activities, 4.9% of treated houses were found to be infested by *T. dimidiata*. The percentage of infested houses by department ranged from 3.9% in Madriz and Nueva Segovia to 6.6% in Estelí. Among the 973 communities treated, 383 communities (39.4%) had more than 5% of houses infested by *T. dimidiata*. These were therefore targeted for the second spraying round.

During the first spray round, *R. prolixus* was confirmed in two houses in the municipality of San Ramon, Matagalpa, in February 2013. These houses were in close proximity, and the same construction materials were used in both houses (i.e., wooden frame, tin roofing, dried grass walls, and earthen floor). In these two houses, five specimens of *R. prolixus* were collected, including three adults and two nymphs that were found in the dried grass walls and in a hen's nest under the beds. Four specimens were microscopically analyzed for the presence of *T. cruzi* in their gut contents, but all specimens proved negative. Owing to this finding, all communities in the municipality of San Ramon were targeted for the second round of spraying, to ensure elimination of *R. prolixus*.

In the second spraying round involving 28 municipalities, 44,683 houses were treated in 664 communities (Table 1). Because the second round was extended to communities adjacent to those found to be highly infested in the first spray round, 221 communities were newly involved. As a result, spraying coverage in rural communities reached 89.7%. In the target communities, 2.8% of treated houses were found to be infested by *T. dimidiata*, with a department-level range from 1.8% in Madriz to 3.5% in Estelí. Among the 664 communities treated, more than 5% of sprayed houses were found infested by *T. dimidiata* in 148 (22.3%) communities. No *R. prolixus* was confirmed in the second spraying round.

Cost estimation of insecticide spraying. We calculated separately the cost of insecticide and other operational costs including fuel and daily allowance for sprayers, supervisors, and drivers. According to the JICA project's financial report, etofenprox was procured at US\$40.10/kg in 2010 and alpha-cypermethrin at US\$94.5/kg in 2011–2013. The spraying program database registered that the average amount of these insecticides used per house in 2010–2014 was 267.5 and 64.2 g, respectively. Thus, the calculated cost of insecticide per house was US\$10.73 for etofenprox and US\$6.07 for alpha-cypermethrin.

With respect to operational costs, the MoH appropriated 30 Nicaraguan córdoba (C\$) per 1-L diesel. The daily allowance for sprayers, supervisors, and drivers was C\$150 per day, according to MoH regulations. When accommodation was necessary, C\$200 was added to the daily allowance. For spraying activities in the first semester of 2013, in which 41,493 houses were to be sprayed, the MoH disbursed a total of C\$180,000 for fuel. Total daily allowance was C\$3,011,400, C\$501,900, and C\$90,000 for sprayers, supervisors, and drivers,

FIGURE 2. Data flow of entomological evaluation to assess effectiveness of two rounds of insecticide spraying. Paired data linked by two-way arrows were statistically analyzed. I.I. represents house infestation index (number of houses infested by *Triatoma dimidiata*/number of houses examined).

FIGURE 3. Trends of *Triatoma dimidiata* house infestation index before and after spraying in 293 communities with a single or double spraying round. Numbers in graph area are number of houses infested/investigated.

respectively. Thus, the operational cost per house was estimated to be C\$91.20, that is, US\$3.80 at the 2012 average exchange rate. In sum, the total cost per house, including insecticide, fuel, and daily allowance, was US\$14.53 for etofenprox and US\$9.87 for alpha-cypermethrin.

Entomological evaluation. Figure 2 shows the data flow for entomological evaluation. We identified 307 communities that were assessed in the 2010 baseline survey and then targeted for the first round of the spraying program. The pretreatment house infestation index of *T. dimidiata* in these 307 communities was 17.0% (725/4,248 houses). During the first spray round, 14 communities dropped out, that is, spraying activities or entomological evaluation were not conducted. Among 293 communities included in the first treatment round, 172 communities proceeded to the second round and no communities dropped out. Thus, among 307 communities selected for entomological evaluation, 172 were sprayed twice, 121 were sprayed only once, and 14 were dropped out.

After the first spray round, we observed a substantial decrease in the *T. dimidiata* house infestation index (Figure 2). In the communities targeted for the first entomological evaluation, this index was dramatically reduced from 17.0% to 3.0% (122/4,049). The difference in house infestation index before and after first round spraying was statistically significant ($P < 0.0001$). In contrast, the second entomological evalua-

tion in 172 communities revealed that the house infestation index of *T. dimidiata* had increased slightly from 3.4% (80/2,346) to 4.4% (102/2,324). However, the difference was not statistically significant ($P = 0.21$). A similar increase in this index was also seen at the second entomological evaluation in those communities where a second spray treatment was not applied (Figure 3).

Table 2 provides details of the entomological evaluation by department. Although this evaluation is not designed for cross-departmental comparison, the infestation level of *T. dimidiata* in Jinotega was found to be higher than the other four departments for pre-spray as well as post-spray indices. Longitudinal trends of infestation indices were similar among the five departments over time. In the first entomological evaluation, we observed that the house infestation index was reduced from 11.7–23.8% to 2.1–5.6%. In the second evaluation, the house infestation index increased slightly, except in Nueva Segovia. In both the first and second entomological evaluation, intradomestic areas were found to be more infested by *T. dimidiata* than peridomestic areas. The average time lapse between insecticide spraying and entomological evaluation was about 4 months in both rounds.

Space-time analysis. In Figure 4, we plotted 279 communities where baseline, first, and second entomological evaluations were conducted. We could not represent 14 communities owing to missing or inaccurate geographical coordinates. The left map (Figure 4A) shows all plotted communities that were infested by *T. dimidiata* at the baseline survey, among which some had a house infestation index of more than 25%. The middle and right maps (Figure 4B and C) show the geographic distribution of communities with *T. dimidiata* infestation index at the post-spray evaluations. The space-time analysis identified eight clusters (demonstrated as red circles in the map [Figure 4A]) where the house infestation of *T. dimidiata* are most likely to happen across space and time. These clusters are located around the communities with high pre-spray infestation level. The χ^2 test confirmed the same trends (Tables 3 and 4): initial house infestation of more than 25% is significantly associated with reinfestation at the first entomological evaluation ($P = 0.030$); reinfestation at the first entomological evaluation is also associated with reinfestation at the second evaluation ($P = 0.014$).

DISCUSSION

The spraying program described here was implemented systematically at large scale with an expected result of reduced

TABLE 2
House infestation index of *Triatoma dimidiata* before and after insecticide spraying, by department in Nicaragua, 2010–2014

Department	Baseline survey (307 communities)		Evaluation 1 (293 communities sprayed in the first spray round)					Evaluation 2 (172 communities sprayed in the second spray round)				
	No. of houses examined	Overall infestation index (%)	No. of houses examined	Infestation index (%)			Mean time lapse in days (range)*	No. of houses examined	Infestation index (%)			Mean time lapse in days (range)*
				Domestic	Peridomestic	Overall			Domestic	Peridomestic	Overall	
Estelí	1,638	15.7	1,624	1.8	0.4	2.3	131.1 (61–292)	808	3.5	1.4	4.8	118.6 (41–166)
Jinotega	609	23.8	462	4.1	1.5	5.6	186.8 (44–417)	311	4.8	2.9	7.7	160.2 (103–219)
Madriz	393	11.7	374	1.6	0.5	2.1	141.9 (99–192)	343	1.5	1.5	2.9	239.2 (79–372)
Matagalpa	924	18.0	905	2.4	0.3	2.8	120.5 (79–170)	547	3.3	0.4	3.7	102.4 (63–145)
Nueva Segovia	684	16.1	684	2.6	1.2	3.8	123.5 (92–201)	315	2.2	0.6	2.9	109.2 (92–131)
Total	4,248	17.0	4,049	2.3	0.7	3.0	136.3 (44–417)	2,324	3.1	1.2	4.4	131.6 (41–372)

*Time lapse in days between insecticide spraying and entomological evaluation.

FIGURE 4. Geographical distribution of 279 communities where (A) baseline survey (2010), (B) first entomological evaluation (2011–2013), and (C) second entomological evaluation (2012–2014) were conducted for *Triatoma dimidiata*. The red circles in the map (A) are the clusters identified by space–time analysis (P value < 0.05). Only clusters smaller than a circle with a 10-km radius are reported.

vector infestation. Although the first spray treatment and entomological evaluation were conducted at different points in time owing to limited financial resources during 2010–2012, spraying ultimately covered 34 municipalities among which 23 completed two rounds each of spraying and entomological evaluation. A total of 78,623 houses were sprayed at least once, and the cumulative total of treated dwellings reached 110,883 in the two rounds of spraying. Considering the risk-driven strategy to identify treatment needs and the results of entomological evaluation in the selected communities, we can definitely assume that the spraying program had a strong impact on controlling indoor populations of *T. dimidiata* and reducing the transmission risk of Chagas disease in these five departments of Nicaragua.

Entomological evaluation demonstrated that house infestation levels of *T. dimidiata* were drastically reduced after the first insecticide treatment, from 17.0% to 3.0%. Although the pre–post design used does not allow us to determine exact causality, we can strongly infer that the observed reduction of *T. dimidiata* can be attributed mainly to the insecticide spraying. Apart from chemical control with insecticide, populations of *T. dimidiata* could be influenced by improvements in housing or by climate events, such as hurricanes.^{28,29} However, no such large-scale socioeconomic or environmental changes were seen during 2010–2014. To the best of our knowledge, the insecticide spraying program

was the only intervention during this period that could contribute widely to the large reduction in domestic populations of *T. dimidiata*.

By contrast, we found no significant changes in *T. dimidiata* house infestation levels after the second spray treatment. Rather, the observed infestation levels had increased slightly in both treated and non-treated communities at the second entomological evaluation (Figure 3). The reason for the increased index could be mainly owing to the limited sensitivity of the man-hour manual search. Monroy and others compared the number of *T. dimidiata* found by the man-hour search method with that found after demolishing an entire house and showed that only 7.0% of the total bugs present could be found by the man-hour method.²⁴ This manual searching technique involves technical bias owing to inspectors' motivation and skill. It is possible that in our study, those bug inspectors who performed the first entomological evaluation had improved their bug searching skills by the second evaluation.

The results of the second entomological evaluation suggest that large-scale insecticide spraying would not be effective where infestation levels are relatively low. A previous study in Guatemala showed that multiple rounds of insecticide spraying was necessary to reduce the *T. dimidiata* infestation index from 40% to 5% or less.¹⁵ When the initial infestation index was around 20%, a single spraying was sufficient to reduce

TABLE 3

Relationship between pre-spraying *Triatoma dimidiata* house infestation index and reinfestation at the first entomological evaluation

No. of communities		Reinfestation at the first entomological evaluation		Total
		Not confirmed	Confirmed	
Pre-spray house infestation index	< 25%	156	51	207
	≥ 25%	54	32	86
	Total	210	83	293

χ^2 test $P = 0.030$

TABLE 4

Relationship between reinfestation at the first and second entomological evaluations

No. of communities		Reinfestation at the second entomological evaluation		Total
		Not confirmed	Confirmed	
Reinfestation at the first entomological evaluation	Not confirmed	148	62	210
	Confirmed	46	37	83
	Total	194	99	293

χ^2 test $P = 0.014$

the infestation index below 5%. In our study in Nicaragua, the initial infestation index was 17.0% on average; thus a single spray treatment would have been sufficient to reduce the infestation level below 5%. However, the long-term effect of multiple spraying should be examined. Hashimoto and others¹⁵ reported recovery of the *T. dimidiata* infestation index after a single spraying. Even if the second treatment is not effective in reducing the infestation index when the initial infestation level is low, it may have long-term impacts in suppressing reinfestation by *T. dimidiata*. Longitudinal monitoring is necessary to understand the reinfestation patterns in communities with single and multiple spray treatments.

With respect to economic aspects, the cost of insecticide spraying for Chagas disease vector control remains a financial burden in Central America. In a previous experience in Guatemala, the cost of spraying per house was US\$9.12, which included the cost of insecticide (deltamethrin or beta-cyfluthrin), sprayers' salaries, fuel, and vehicle maintenance.¹³ A simple comparison with our cost estimates in Nicaragua is inappropriate because we included labor costs for supervisors and drivers and did not include costs for vehicle maintenance. However, the cost per house in Guatemala was similar to our cost estimation with alpha-cypermethrin, which was US\$9.87 per house. In Nicaragua, the cost of large-scale spraying for Chagas disease vector control was not affordable for the MoH, and the procurement of insecticide depended entirely on external funding. As Nakagawa and others¹³ observed, the cost of insecticide plays a crucial role in lowering the entire cost of spraying operations.

Triatoma dimidiata has a high capacity of reinfesting human dwellings after insecticide spraying in Central America.^{15,30} Understanding the mechanism of reinfestation is crucial to formulating an effective post-spray control strategy for *T. dimidiata*. Theoretically, reinfestation can occur in two ways: 1) vectors survive the insecticide treatment or 2) vectors migrate to treated houses after spraying.²⁵ The first option of survival is mainly owing to insufficient coverage or unskilled insecticide spraying techniques, including poor dilution of insecticide, inadequate water pH in which the insecticide is prepared, and poor penetration of insecticide in the wall cracks where *T. dimidiata* lives. A repellent effect of insecticide could be a reason of survival, enabling vectors to detect residues of insecticidal component and escape to sites without residues, such as deep wall cracks or ceiling. The vector's resistance to pyrethroid is another possible reason for survival, as was the case for *T. infestans* in northern Argentina.³¹ However, there is no evidence in Central America of *T. dimidiata* developing insecticide resistance.

Regarding the second option of reinfestation by vector migration, the pattern of reinvansion to sprayed houses by *T. dimidiata* could vary in sources and ways of migration. *Triatoma dimidiata* can come from the peridomestic ecotopes and even from other houses or adjacent communities.^{32,33} Sylvatic population of *T. dimidiata* might also be a source of reinvansion. *Triatoma dimidiata* can move by active transportation (i.e., flying) or passive transportation (i.e., carried by humans, animals, farming implements, or tacks). In addition, capacity of reinfestation may differ widely among subgroups of *T. dimidiata*.^{10,34} Given such complex mechanisms, the effective control of reinfestation is difficult without understanding the pattern of reinfestation of *T. dimidiata* in each local setting.

In this study, we also observed infestation by *T. dimidiata* after both the first and second rounds of spraying. The entomological evaluations found 2- to 3-fold higher numbers of infested houses in intradomestic ecotopes than in peridomestic ecotopes (Table 2). This result may suggest that more reinfestant vectors were survivors within houses evaluated prior to spraying; however, this does not exclude the possibility of vector migration after treatment. It is likely that the reinfestant vector population would be a mix of surviving and reinvading vectors, but further analysis is not possible using the available data in this study. For this problem, genetic or morphometric studies will provide valuable information, comparing the spatial patterns and population structures of vectors before and after insecticide spraying. For instance, a morphometric study in Chaco Province of Argentina suggested that reinfestant *T. infestans* came from external sources because they were significantly different from the pretreatment vector population.³⁵ Similar studies should be encouraged for improving understanding of the reinfestation pattern of *T. dimidiata*.

Figure 4, although our data are patchy because of the limited number of communities investigated, shows that the communities where reinfestation was confirmed are not uniformly distributed. Instead, the reinfested communities seem to be gathered in some specific areas. The space-time analysis identified high-risk clusters around communities highly infested at the baseline survey. Tables 3 and 4 also suggest that communities with high pre-spray infestation indices are likely to be reinfested after spraying, and further reinfestation could occur in such communities. These results are consistent enough to lead a conclusion that the reinfestation by *T. dimidiata* is more likely to happen in some spatial clusters where the inherent infestation level is high. Existence of such clusters vulnerable to the *T. dimidiata* reinfestation is compatible with the previous spatial study in Guatemala.¹⁶ Probably in the high-risk clusters, the communities share the similar environmental or housing conditions and exchange vectors constantly among them. To address the reinfestation of *T. dimidiata* efficiently, the MoH's vector control program should pay more attention to the areas where some communities with high pre-spray infestation level are gathered.

The present spraying program provided strong evidence toward the elimination of *R. prolixus* in the targeted five departments. In Nicaragua, after large-scale spraying activities for controlling *R. prolixus* in 1998–2000, this species was sporadically detected in 2002–2009.¹⁸ This implies that the initial spraying program left some communities untreated and vulnerable to probable infestation with *R. prolixus*. The spraying program in 2010–2014 complemented the initial program to expand the geographic control coverage. As a consequence, *R. prolixus* was still detected in one community from the municipality of San Ramon during the first spraying round in 2013. The absence of *R. prolixus* was confirmed in the second round, which included all communities in this municipality. Yet it remains uncertain if the control coverage was sufficient to detect all *R. prolixus* in the region. Entomological surveillance must be sustained to ensure elimination of *R. prolixus* in Nicaragua.

Further challenges for preventing vector-borne transmission of *T. cruzi* by *T. dimidiata* include implementing multilevel approaches. At the operational level, a single intervention relying only on indoor insecticide spraying is unsuitable for

controlling *T. dimidiata*, which can repeatedly reinfest human dwellings. There is a need to seek an optimal mix of chemical and ecological approaches, such as improving dwellings with locally available materials.²⁸ In addition, encouraging certain behaviors among community members, such as self-fumigation of dwellings or relocation of domestic animals away from the house, could offer easy anti-triatomine solutions.³⁶ At the strategic level, the classical three-phase vector control strategy, that is, preparation, attack, and surveillance,⁵ is no longer appropriate in scenarios where *T. dimidiata* is distributed widely at low levels of infestation. The attack phase of this strategy (i.e., large-scale insecticide spraying) is not cost-effective or affordable for Central American settings. An alternative strategy is to first implement community-based vector surveillance in all areas suspected of *T. dimidiata* infestation. Such vector surveillance, once integrated into primary health-care services, can be administrated in a sustainable way and will enable detection of vector infestation foci.³⁷ At the international policy level, the current common goal that emphasizes the interruption of vector-borne transmission is no longer suitable for controlling *T. dimidiata*. Policy change is needed, which adds weight to sustainable control rather than the interruption of disease transmission.³⁸

In conclusion, we demonstrated substantial effectiveness of large-scale insecticide spraying to reduce house infestation levels of *T. dimidiata*. However, because of frequent reinfestation by *T. dimidiata* as well as the financial burden, such large-scale spraying is not a deliberate strategic option, particularly when house infestation levels of *T. dimidiata* are low. Further research will help to gain a thorough understanding of the mechanisms of *T. dimidiata* reinfestation. Operational, strategic, and policy innovations are necessary, to implement more cost-effective and sustainable vector control programs.

Received June 2, 2015. Accepted for publication August 20, 2015.

Published online September 28, 2015.

Acknowledgments: We appreciate the laborious efforts of those who participated in the field operations of spraying and entomological evaluation. We also thank the householders who kindly accepted the spraying activities. Thanks to Toshihiko Sunahara for technical advices on space-time analysis.

Financial support: The vector control program described in this article was conducted with financial contributions from the Embassy of Japan in Nicaragua, Japan International Cooperation Agency (JICA), and Pan American Health Organization (PAHO).

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