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Effects of partial housing improvement and insecticide spraying on the reinfestation dynamics of *Triatoma infestans* in rural northwestern Argentina

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Abstract

The long-term effects on domiciliary reinfestation by *Triatoma infestans* of smoothing the plaster of indoor walls prior to insecticide application (in Amamá village) relative to only insecticide application (in Trinidad–Mercedes villages) were evaluated in rural northwestern Argentina from 1992 to 1997. All domestic and peridomestic areas of each house were sprayed with 2.5% suspension concentrate deltamethrin at 25 mg/m^2 in October 1992, and infestations were assessed by various methods every 6 months. Domiciliary infestation decreased from 72–88% in 1992 to 6–17% in late 1995, to increase moderately thereafter without returning to baseline rates. Peridomestic sites were the first in becoming reinfested, and reached more abundant *T. infestans* populations than domiciliary areas. Domiciliary infestation rates and bug abundances were not significantly different between communities during surveillance. Domiciliary infestation rates in well-plastered houses were very low (5–9%) and approximately stable until 1996, but in houses with regular or bad plaster they consistently increased from 5 to 19–21% in both communities. Logistic multiple regression analysis showed that the likelihood of domestic infestation assessed through householders' collections was significantly and positively associated with the occurrence of an infested peridomestic site in the respective house, the occurrence of high-density domestic infestations before interventions, and well-plastered walls in 1996. Combining insecticide spraying and partial improvement of walls controlled domestic infestations and transmission of *Trypanosoma cruzi* effectively, but was not sufficient to eliminate *T. infestans* from the study area or increase the effectiveness of careful chemical control.

Keywords: *Triatoma infestans*; Chagas disease; Control; Surveillance; Insecticide; Environmental management

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1. Introduction

Triatoma infestans, the principal vector of *Trypanosoma cruzi*, is the target of an insecticide-based elimination program known as the Initiative of the Southern Cone Countries (Schmunis et al., 1996). Progress towards elimination in Uruguay, Brazil and Chile has been accompanied by more limited success in western and northern Argentina. In particular, the control of *T. infestans* has been historically more difficult in the northwestern province of Santiago del Estero (Segura et al., 1999), where it could not be eliminated after a district-wide spraying of deltamethrin of all rural houses and peridomestic sites (blanket spraying), surveillance and repeated treatments over 5 years (Paulone et al., 1988; Chuit et al., 1992). In Amamá, in the absence of subsequent surveillance and effective control measures, domestic reinfestation increased exponentially until returning to pre-treatment infestation levels in 3–5 years (Gürtler et al., 1994). Domestic reinfestation was significantly associated with the abundance of *T. infestans* in bedrooms just before deltamethrin spraying, and the surface structure of indoor walls (Gürtler et al., 1994). These studies showed the limitations of standard chemical control and suggested the need for more permanent environmental management measures aiming at a sustainable control or elimination program.

Plastering of walls reduced the population size of *T. infestans* in one house in Brazil (Schofield and Marsden, 1982) and could prevent house recolonization (Schofield and Matthews, 1985), but this has not been tested yet at a community-wide scale. Very few studies (Organización Panamericana de la Salud, 1998; Alfred Cassab et al., 1999; Rojas de Arias et al., 1999) have evaluated the sole or joint effects of housing improvement and spraying insecticides on the domiciliary reinfestation by triatomine bugs. These studies did not provide a clear conclusion regarding whether the addition of house modification measures increased the effectiveness of insecticide spraying. As part of a larger project on the transmission dynamics and control of Chagas disease (Gürtler et al., 1998, 1999; Cohen and Gürtler, 2001), we sought to assess the relative effects of plastering indoor walls prior to deltamethrin spraying on the infestation, colonization and domiciliary abundance of *T. infestans* in two neighboring rural communities over 5 years post-intervention (p.i.). In addition, we describe the process of housing improvement carried out with community participation, and the risk factors associated with domestic reinfestation. This is the first intervention study in which the long-term effects of a combined control program on *T. infestans* populations were compared with insecticide spraying. The effects on *T. cruzi* prevalence in bugs, people and dogs will be treated separately.

2. Materials and methods

2.1. Study area

Field studies were carried out in the rural villages of Amamá, Trinidad, Mercedes, Villa Matilde and Pampa Pozo (27°S, 63°W), Province of Santiago del Estero, Argentina. These communities were located in a semiarid plain with hardwood forest of ‘quebracho’ under exploitation. The area and their history of infestation by *T. infestans* were described before (Gürtler et al., 1992, 1994).

Most houses were made of adobe walls and thatched roofs, with one or two adjacent bedrooms and a front veranda 5–10 m wide. These areas shared a common roof and will be referred to hereinafter as domestic or domiciliary areas. The peridomestic area consisted of a patio and three to eight peridomestic structures (store rooms, kitchen, corrals, pieces of wood, trees) separated from human habitations (Cecere et al., 1997a). All houses were identified with a numbered plaque and mapped in 1992.

The study communities were selected because they were the site of a long-term study on the ecology and epidemiology of Chagas disease; the research team had a established relationship with householders, and the houses could be accessed through paved or dirt roads. Economic, logistic and practical constraints excluded the possibility of considering replicate villages of similar size within a 50 km radius. The combined control program was carried out in Amamá because of the anticipated community compliance and the presence of a local construction worker accepted by the community.

3. Study design

The study comprised (1) baseline surveys of triatomine infestation, dog and human seroprevalence carried out in March–October 1992; (2) interventions in August–October 1992; and (3) surveillance of triatomine infestations and dog seroprevalence in 1993–1997 (Gürtler et al., 1999; Cecere et al., 1999; Castañera et al., 1998). In the baseline survey, a total of 71 houses were visited to search for triatomine bugs in all bedroom areas and peridomestic structures, and householders were asked about demographic and environmental risk factors (Cecere et al., 1997b, 1998). The prevalence of *T. cruzi* in the domestic bug, dog and human populations was 49, 65, and 34%, respectively (Gürtler et al., 1998).

In the intervention phase, in August 1992 householders from Amamá were proposed to improve the plaster of indoor walls of their houses prior to the insecticide spraying of all domestic and peridomestic areas conducted by the National Chagas Service (NCS). After house-to-house visits, a meeting open to all members of the community was held at the school to explain the program rationale and how this was expected to benefit householders. Plastering of walls was to be done before the spraying, instead of immediately after, to allow the residual effects of deltamethrin. House-dwellers were offered the assistance of two construction workers supported by the research project, but they were to contribute at least by carrying water and soil. All families willing to participate in the program signed an informed consent. House improvements began on August 1992 and lasted 50 days. The construction workers always used cement and lime-based plasters. Householders plastered walls using different mixtures of materials (mud, water, cement, ashes, sand, dry grass or horse dung). Residents from Trinidad and Mercedes were not stimulated to plaster the walls of their houses.

The first assessment of the state of wall plasters was carried out during spraying operations in October 1992. The materials employed in roofs and walls, and the state of wall plasters were recorded; a photograph was taken to document the different types of structures. Thatched roofs were classified as composed entirely of 'simbol' (*Pennisetum* sp.), partly of 'simbol', and without 'simbol', implying the use of other brushwood materials such as 'jarilla' (*Larrea* sp.). The state of plasters was categorized in three levels of deterioration though direct observation by MCC: good (no crevices), regular (some crevices or partly without plaster), and bad (abundant cracks or without plaster). Cracks or crevices were taken to be a place that could serve as a refuge for a triatomine nymph or adult (i.e. at least 2 mm wide and 2 mm long). Follow-up surveys were done in May and October–December from 1993 to 1997 by MCC and/or DMC. Householders were asked about recent housing improvements, the domestic use of insecticides (type, frequency, mode and date of last application), the place where chickens usually nested, and the numbers of fowls and corral animals (goats, sheep, cows, horses and mules) owned by the family. Householders' habit of allowing chickens to brood indoors was classified as domiciliary or peridomestic (Cecere et al., 1997b).

All houses and their peridomestic structures (including two schools, a church, police post, and dilapidated huts) were sprayed in October 1992 (Cecere et al., 1997a). Six NCS professional spraymen applied a total of 69.6 l of 2.5% suspension concentrate deltamethrin (K-Othrina, Farquimia, Argentina) at an intended rate of 25 mg active ingredient per m^2 of sprayed surface using Laska spray pumps (Laska, Argentina) with Teejet 8002 tips. In November–December 1992, the effectiveness of spraying was assessed and the detected peridomestic foci of *T. infestans* were immediately sprayed with insecticides as before. All 13 houses of the neighboring villages of Villa Matilde and Pampa Pozo (a possible source of reinfestation for Trinidad–Mercedes) were sprayed between October 1993 and May 1994.

The surveillance phase spanned from December 1992 to 1997. Every 6 months, each house was visited to monitor domestic and peridomestic reinfestation, assess environmental and demographic attributes by direct observation and a questionnaire, and carry out selective insecticide sprays. The vector collection methods used were described before (Gürtler et al., 1999). In mid-December 1992, an average of 3 (range, 2–5) sensor boxes (Biosensor, Biocientífica de Avanzada®, Buenos Aires) was placed indoors or in the veranda of each house. Each 12 months from October 1993 to December 1997, three skilled bug collectors from NCS searched for triatomines all bedroom and peridomestic areas using 0.2% tetramethrin in isobutane and an organic solvent (Icona, Buenos Aires) as an irritant agent. During 30 min per house, two men searched bedrooms (1 person-h) while another man searched peridomestic sites (0.5 person-h per house). Additional searches for bugs were carried out in peridomestic sites in each May from 1995 to 1997 (0.5 person-h per house). In May 1993 and thereafter, a labeled self-sealing plastic bag was provided to each household to contain any triatomine that they could capture in domestic or peridomestic sites. At each visit, house-dwellers were asked for their bag collections, the place where they had captured the bugs, and the presence or sighting of triatomines in bedrooms or peridomestic areas. All bugs were later identified to species and stage at the field laboratory as described elsewhere (Canale et al., 2000).

The term 'infested' was taken to mean the finding of at least one live or moribund *T. infestans* by a given method or combination of methods. The finding of one or more nymphs was used as a colonization index (World Health Organization, 1991). If a house is colonized it is necessarily infested, but the reverse is not true. A house was 'invaded' when a single adult bug (or very few) was found in it at a given survey. The presence of triatomine-like fecal smears in sensor boxes was not considered conclusive evidence of infestation by *T. infestans* because there were other species of triatomines that invaded the house and left triatomine dejecta, and because visual inspection of triatomine-like dejecta had a 60–67% false positive rate (Gürtler et al., 1999, 2001a).

From 1993 to 1995, only sites with at least one *T. infestans* adult and nymph, not other triatomines, were treated selectively with deltamethrin by NCS staff as before (Cecere et al., 1999). In November 1995, to confirm infestations in houses that had had triatomine fecal smears in sensor boxes in the preceding 12 months or whose residents reported domestic infestations, bedrooms of 16 Amamá houses and 14 Trinidad–Mercedes houses were treated with one or two insecticide fumigant canisters per room or sprayed with deltamethrin and the knocked down bugs collected (Gürtler et al., 1999). Surveillance activities were transferred to the communities through six workshops conducted from late 1995 to 1996 (Cecere et al., 1999). In this period, the capture of one *T. infestans* bug of any stage was considered sufficient evidence to treat all domestic and peridomestic areas.

4. Data analysis

The evaluation of the effects of 1992 interventions is divided into the 1993–1995 period, when Amamá had more houses with well-plastered walls than Trinidad–Mercedes and very few selective insecticide treatments were carried out, and the 1996 period, when both communities had a similar distribution of wall surface structure and insecticide sprays were frequent.

The relationship between domiciliary infestation or colonization by *T. infestans* and potential risk factors was studied using the logistic–binomial random effects model for distinguishable data matched by community (Egret, 1993), which may include a random effects parameter that measures a residual cluster effect on the probability of being infested. Multiple linear regression and backward stepwise elimination were implemented using STATISTICA (release 4.3) to find the best set of predictors describing variations among log-transformed numbers (plus one) of domestic *T. infestans*. The response variables (domestic infestation, colonization and abundance of *T. infestans*) over a given time period were determined by the pooled result of timed manual collections and sensor boxes, and separately, by householders' collections (see below). Bug collections in domestic areas of a given house over a given time period were pooled.

All but one of the explanatory variables were treated as 'dummy' variables: domiciliary abundance of *T. infestans* (zero to ten bugs vs. more than ten bugs) estimated by timed manual capture (in March 1992) or knock-down (in October 1992); infestation or peak abundance of *T. infestans* in peridomestic areas of the respective house (assessed by timed manual capture or householders' collections in a specified period); reported use of insecticides in domestic areas; hens nesting indoors; roof type (totally 'simbol' vs. partly or no 'simbol'); and state of wall plaster (good vs. bad or regular). Records of the state of wall plaster, hens nesting indoors, and insecticide use obtained in November 1995 and November 1996 were used for 1993–1995 and 1996, respectively. Data missing in November were substituted by those collected in May of the same year. Only houses that had been sprayed with deltamethrin in 1992, had permanent residents and whose domestic infestations were evaluated at least by timed collections and sensor boxes in November–December of each year were included in the analysis (84 in 1993–1995, and 88 in 1996).

5. Results

5.1. Baseline phase

T. infestans was collected by timed manual searches in domestic or peridomestic sites from 42 (89%) houses in Amamá and 24 (100%) houses in Trinidad–Mercedes in March 1992. The prevalence of infestation or colonization by *T. infestans* did not differ significantly between Amamá and Trinidad–Mercedes both at domestic and peridomestic sites regardless of the vector collection method used (χ^2-tests with 1 df, $P \geq 0.15$), neither did bug abundance (Mann–Whitney tests, $P > 0.3$) (Table 1). The log-transformed domiciliary abundances of *T. infestans* (plus one) estimated by timed manual collection (in March, x) and knockdown collections after deltamethrin spraying (in next October, y) were correlated in a highly significant way ($r = 0.689$; $P < 0.001$; $y = 0.1002 + 0.702x$; $n = 68$).

Among environmental and demographic factors (Table 2), Amamá had significantly fewer houses with all or part 'simbol' roofs ($4+6=10\%$) than Trinidad–Mercedes ($20+22=42\%$), and fewer goats per house. Both communities did not differ significantly in household size, numbers of dogs and chickens per house, frequency of allowing chickens to nest in bedrooms, and reported use of insecticides in domestic areas. Although both communities had 25% of houses with well-plastered walls (Fig. 1A), Amamá had more houses with wall plasters in bad condition (30%; 14 of 47) than Trinidad–Mercedes (13%; three of 24) but not significantly so ($\chi^2 = 0.0$; df $= 1$; $P = 0.96$). Child or adult seropositivity rates for *T. cruzi* did not differ significantly by community in a logistic multiple regression analysis (Gürtler et al., 1998).

5.2. Monitoring of wall plasters

Thirty (60%) households from Amamá participated in improving their houses (improved houses). In six (20%) of these houses the residents plastered the walls by themselves, while in the remainder they were assisted by the construction workers. Among the 20 unimproved houses from Amamá, 55% had good wall plasters that did not need improvement, and 25% were occupied transiently. Unimproved Amamá houses had a marginally smaller household size and significantly fewer dogs and goats per house than improved Amamá houses.

The percentage of improved Amamá houses with well-plastered walls decreased steadily from 83% in October 1992 to 16% in December 1997 (Fig. 1B), whereas in Trinidad–Mercedes there was no significant time trend (Fig. 1A). The frequency of unimproved houses that had well-plastered walls remained stable over years (Fig. 1B). Very soon after housing improvements, in October 1992, the percentage of houses with well-plastered walls in Trinidad–Mercedes (34%; 14 of 41) was significantly lower than among improved (83%, 25 of 30, $\chi^2 = 16.93$; df $= 1$; $P < 0.001$) or all Amamá houses (72%, 36 of 50, $\chi^2 = 13.04$; df $= 1$; $P < 0.001$). This pattern persisted for 2.5 years p.i.

Table 1
Prevalence of infestation and colonization, and abundance of *T. infestans* by community, capture method and collection site

Community	Capture method	Number of houses surveyed	Percent infested[a]		Percent colonized[a]		Median number of bugs per house (first–third quartiles)	
			Domicile	Peridomicile	Domicile	Peridomicile	Domicile	Peridomicile
Amamá[b]	TMC	47	72	47	72	47	11 (0–37)	0 (0–11)
	KD	55	62	ND	44	ND	2 (0–9)	ND
Trinidad–Mercedes	TMC	24	88	50	79	38	6 (1–13)	0.5 (0–5)
	KD	36	67	ND	33	ND	3 (0–19)	ND

Amamá, Trinidad–Mercedes; March (timed manual collection, TMC) and October (knock-down with deltamethrin, KD) 1992. ND, not done.
[a] Infestation was taken to mean the finding of at least one *T. infestans* of any stage. Colonization means the finding of at least one nymph of *T. infestans*.
[b] A total of 129 *T. infestans* were captured in 28 of 45 Amamá houses using sensor boxes in March 1992, and 24 of these houses were colonized.

Table 2
Distribution of Amamá and Trinidad–Mercedes houses by environmental and demographic factors

Household attributes	Levels	Number of houses (%)	
		Amamá	Trinidad–Mercedes
Environmental factors			
Type of roof	All simbol	3 (6)	8 (20)
	Partly simbol	2 (4)	9 (22)
	No simbol	45 (90)[a]	24 (59)[a]
Chickens nesting in bedrooms[b]	Yes	18 (36)	21 (51)
	No	32 (64)	20 (49)
Insecticide use[c]	Yes	17 (35)	13 (33)
	No	31 (65)	27 (67)
Demographic factors[d]			
Number of persons per house		5 (3–7)	4 (2–7)
Number of chickens per house		27 (11–40)	20 (10–46)
Number of dogs per house		2 (2–3)	2 (1–3)
Number of goats per house		0 (0–9)[e]	18 (0–26)[e]

Amamá and Trinidad–Mercedes, 1992–1994.
[a] $\chi^2 = 12.17$; df = 1; $P = 0.0005$.
[b] One house from Trinidad–Mercedes with missing data.
[c] Two houses from Trinidad–Mercedes and two from Amamá with missing data.
[d] Number are median and quartiles.
[e] Test of Mann–Whitney, $0.01 < P < 0.05$.

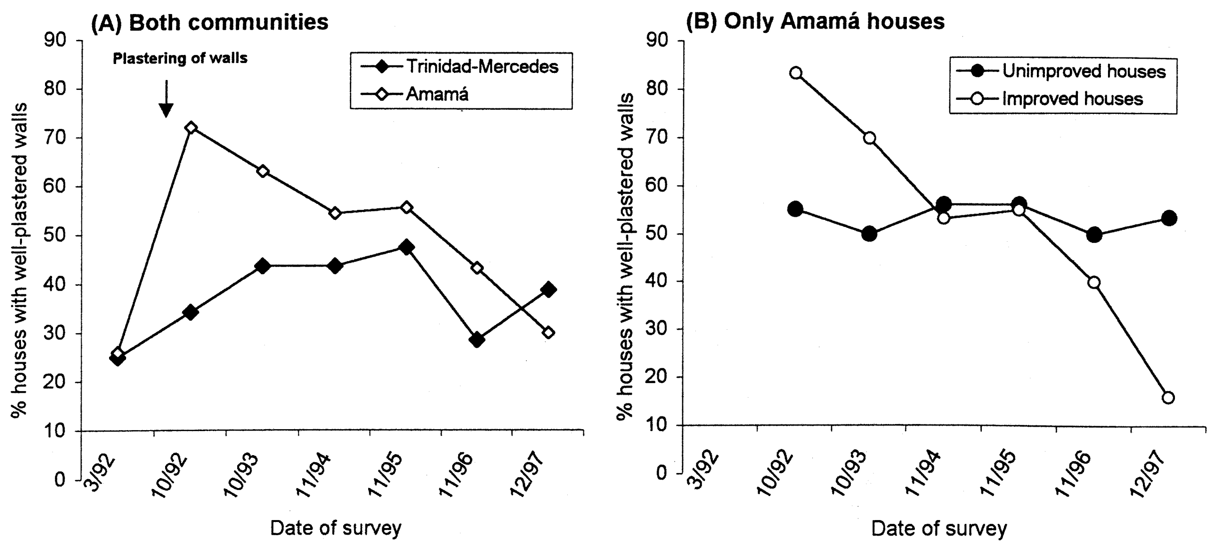

Fig. 1. Distribution of wall plaster state for all houses in Amamá and Trinidad–Mercedes (A) and for improved and unimproved houses in Amamá (B); March 1992–December 1997.

By December 1997, Trinidad–Mercedes had slightly more houses with good plaster (39%, 14 of 36) than Amamá (30%, 12 of 40) ($\chi^2 = 0.77$; df = 2; $P = 0.68$). The proportion of improved houses that still had good plasters by late 1997 was almost identical among those that had or had not received assistance from the construction workers (16 vs. 17%).

Most of the plasters resisted the early formation of crevices, and then suffered a gradual cracking depending on the mixture selected by each household. None of the houses with wall plasters that included sandy soil (five houses), ashes and ground grass or horse dung (four houses), soil–cement mixtures or cement (four houses) cracked evidently at 3 years p.i. Nearly half (55%) of the improved houses had wall plasters in a good state until 1995.

5.3. Temporal variation of reinfestation

The prevalence rates of domiciliary infestation or colonization did not return to baseline rates until 1997 (Fig. 2A and B). Domiciliary infestation decreased from 72–88% in both communities at baseline to 6–17% in late 1995, and thereafter increased moderately. The domiciliary abundance of *T. infestans* followed a similar pattern. The first domestic colonies were found 1.5 years p.i. in Amamá and 3 years p.i. in Trinidad–Mercedes. In peridomestic sites, the infestation, colonization and abundance of *T. infestans* showed an increasing trend until 1997 in Amamá (Fig. 2C) and a more stable pattern in Trinidad–Mercedes (Fig. 2D). Peridomestic colonies of *T. infestans* were first detected 1 year p.i. In Amamá, peridomestic colonization (35%) and infestation (40%) rates in December 1997 were similar to baseline values (43 and 45%, respectively) (Fig. 2C), whereas in Trinidad–Mercedes they were significantly lower (14 and 18%) than at baseline (38 and 50%) (Fig. 2D). The geometric mean ratio of bugs collected by timed manual collections in peridomestic to domestic areas in November–December surveys was always greater than 1 (range, 1.7–4.5) in both communities, except in 1996 in Trinidad–Mercedes. Since the capture effort in peridomestic sites was half of that used in domestic areas, the actual mean ratio was clearly underestimated.

The distribution of the domestic abundance of *T. infestans* per house assessed by timed manual collections (or by all methods) showed a sharp contrast between 1992 and succeeding years in both communities (Fig. 3). During surveillance, very few bugs were collected in bedrooms and very few houses concentrated the detected infestations. The number of domiciliary *T. infestans* per house was not significantly different between Amamá and Trinidad–Mercedes in 1993–1995 ($H = 2.33$; $P = 0.13$) and 1996 ($H = 1.77$; $P = 0.18$).

The proportion of all houses whose domestic or peridomestic areas were sprayed with deltamethrin at least once by NCS from 1993 to November 1995 was 2% of 50 houses in Amamá, and 4% of 47 houses in Trinidad–Mercedes. The proportion of peridomestic bug colonies detected during 1993–1995 that were sprayed immediately was 25% (one of four) in Amamá and 50% (two of four) in Trinidad–Mercedes. In addition to insecticide fumigant canisters applied in bedrooms in late 1995, from December 1995 to November 1996 the rate of insecticide spraying increased to 14 (28%) houses in Amamá and 12 (26%) houses in Trinidad–Mercedes.

5.4. Wall plaster state and infestation

In well-plastered houses, domiciliary infestation rates assessed by timed manual collections and sensor boxes were approximately stable from 1993–1995 to 1996 in both Amamá (8–9%) and Trinidad–Mercedes (5–8%), but in houses with regular or bad plaster infestation consistently increased from 5 to 19–21% (Fig. 4A). However, the relative odds (OR, odds ratio) of domiciliary infestation by *T. infestans* stratified by community did not differ significantly between wall plaster categories in 1993–1995 (OR = 1.37; Mantel–Haenszel $\chi^2 = 0.11$, df = 1; $P > 0.05$) and 1996 (OR = 1.37; Mantel–Haenszel $\chi^2 = 2.07$, df = 1; $P > 0.05$). Domiciliary colonizations appeared earlier in houses with regular or bad plasters than in well-plastered ones in both communities, and tended to increase from 1993–1995 to 1996. Median domestic bug abundances per infested house were approximately stable over years regardless of wall surface structure and community.

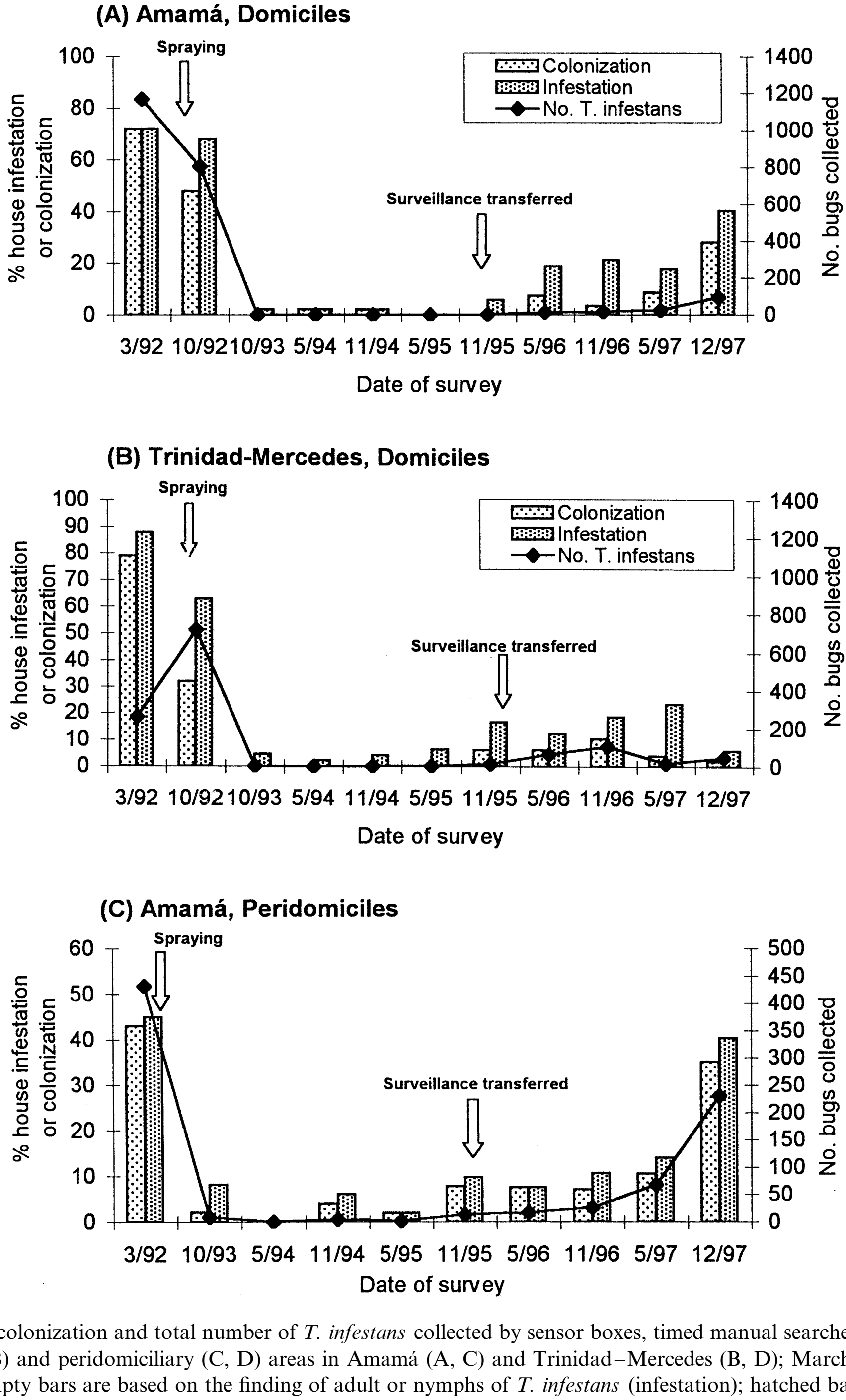

Fig. 2. Infestation, colonization and total number of *T. infestans* collected by sensor boxes, timed manual searches and householders in domiciliary (A, B) and peridomiciliary (C, D) areas in Amamá (A, C) and Trinidad–Mercedes (B, D); March to October 1992–December 1997. Empty bars are based on the finding of adult or nymphs of *T. infestans* (infestation); hatched bars are based on the finding of at least a *T. infestans* nymph (colonization).

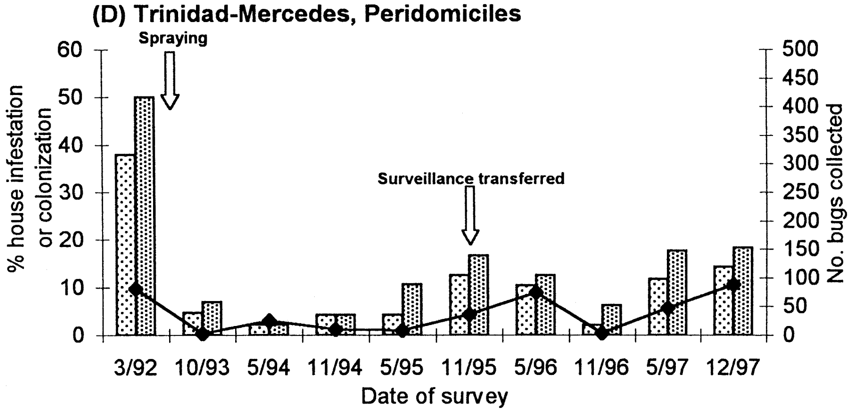

Fig. 2 (*Continued*)

Logistic multiple regression analysis of factors potentially associated with domestic infestation or colonization by *T. infestans* showed that none of the models was significant in 1993–1995 or 1996 (not shown).

When domestic infestation was assessed through householders' bug collections, houses with well-plastered walls showed consistently higher infestation rates than houses with regular or bad plasters in both communities (Fig. 4B). Very few of the positive houses showed concurrent or subsequent evidence of domestic colonization. The annual median capture of domestic *T. infestans* per house only showed a clearly increasing trend from 1993–1995 to 1996 in Trinidad–Mercedes houses with regular or bad plasters. Logistic regression analysis showed that the likelihood of domestic infestation assessed through householders over 1993–1995 was significantly and positively associated with the occurrence of an infested peridomestic site in the respective house ($P = 0.022$) (Fig. 5A). Stepwise linear regression of the numbers of domestic *T. infestans* captured by householders in 1993–1995 only was significantly and positively associated with the peak number of *T. infestans* captured in peridomestic sites in the respective house ($R^2 = 0.10$; $F = 10.4$; $P < 0.0018$). Domestic infestation through householders' bug collections in 1996 (Fig. 5B) was significantly and positively associated with the catch of ten or more *T. infestans* in domiciliary areas (by timed or knock-down collections) before spraying in 1992

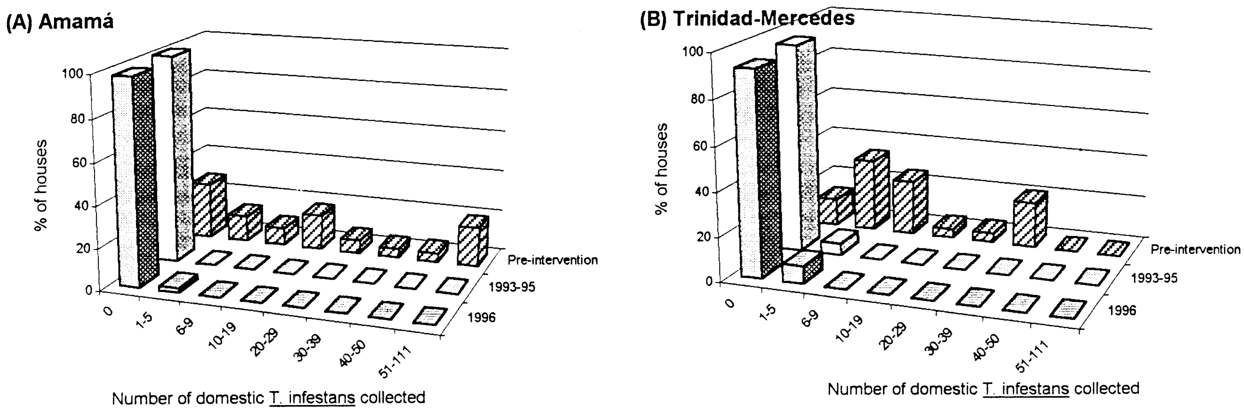

Fig. 3. Distribution of the domiciliary abundance of *T. infestans* by timed manual collections in Amamá (A) and Trinidad–Mercedes (B); March 1992–December 1997.

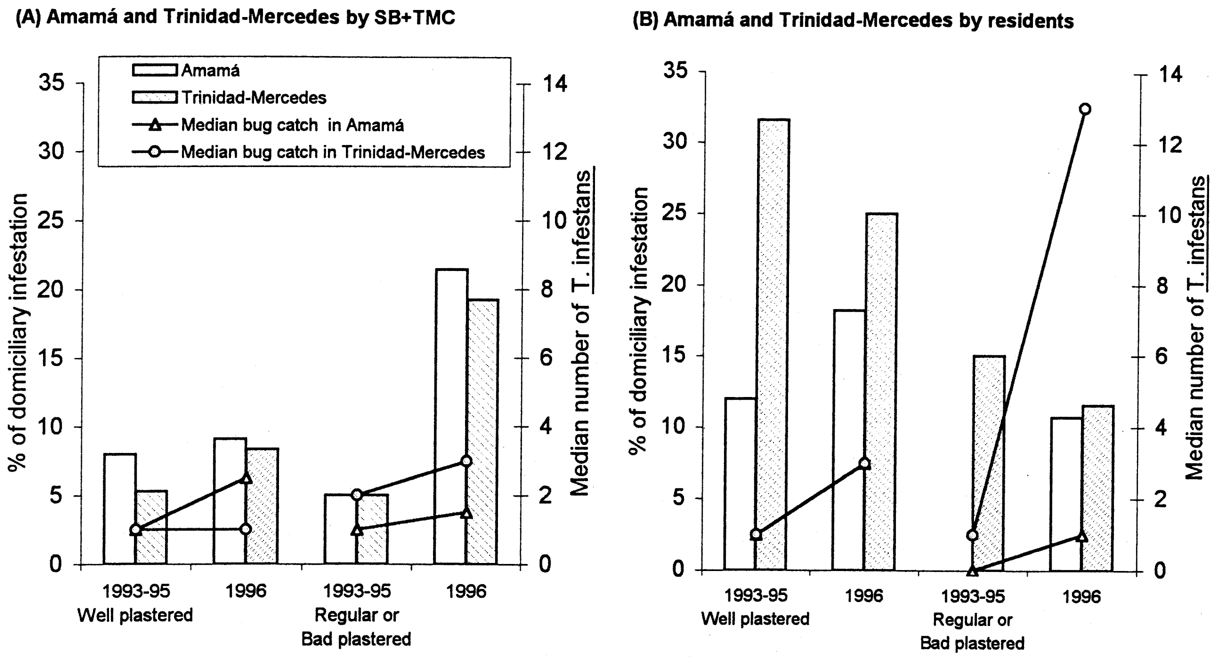

Fig. 4. Infestation (finding of adult or nymphs) and median number (per infested house) of *T. infestans* collected by timed manual collections (TMC) or sensor boxes (SB) (A) and householders (B) in domiciliary areas in Amamá and Trinidad–Mercedes; 1993–1997.

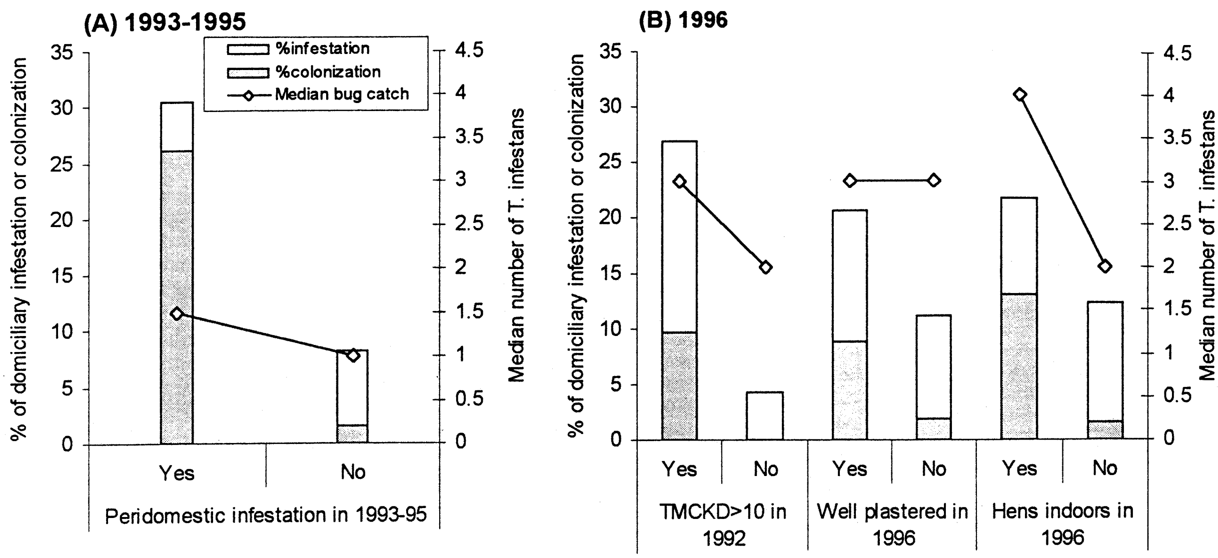

Fig. 5. Risk factors significantly associated with infestation (empty bars), colonization (hatched bars) or median number (per infested house) of *T. infestans* collected by householders in domiciliary areas (Amamá and Trinidad–Mercedes combined) in 1993–1995 (A) and 1996 (B). TMCKD >10 means that the domiciliary abundance of *T. infestans* by timed manual capture or knock-down was more than ten bugs before interventions.

($P = 0.05$), and the occurrence of well-plastered walls ($P = 0.033$). Domestic colonization in 1996 was positively and marginally associated with the presence of hens nesting indoors ($P = 0.06$).

6. Discussion

In the context of a control program with community participation, a single blanket residual spraying of deltamethrin at the standard dose followed by infestation assessments and selective sprays of the detected residual foci nearly eliminated bug infestations for 2–3 years (Cecere et al., 1997a). In spite of close supervision and professional spraying procedures, *T. infestans* resurged thereafter. Selective treatments since late 1995 limited the re-establishment of domestic *T. infestans* populations and brought about a sharp decline in the prevalence rates of *T. cruzi* in *T. infestans* from 40.5% before spraying to 2.4% in 1997 (Cecere et al., 1999), and in the dog population from 65 to 15% in 1996 (Castañera et al., 1998). By late 1996, the intensity of domestic infestations was much lower than at baseline and was aggregated in very few houses, despite peridomestic foci were widespread. The crucial outcome variable for evaluating the merit of plastering walls as opposed to spraying houses with insecticides is the effect on the human prevalence of *T. cruzi* infection. Presumably the size of the bug population is a surrogate measure of the human prevalence of infection, but as we did not allow the domestic bug colonies to continue growing for obvious ethical reasons, the ultimate effects of interventions on domestic bug density cannot be assessed. We conclude that the set of actions taken controlled domestic infestations and transmission of *T. cruzi* effectively but were not sufficient to eliminate *T. infestans* from the study area.

Peridomestic foci were the most likely sources of domestic reinfestation throughout the study. Peridomestic residual foci of *T. infestans* were detected soon after the blanket spraying of deltamethrin in Amamá (Cecere et al., 1997a), Bolivia (Dujardin et al., 1996; Guillén et al., 1997), and Brazil (Pinchin et al., 1980; Oliveira Filho et al., 1986). Although in our study area the residual foci generally were sprayed soon after being detected, the number of peridomestic colonies and mean abundance of *T. infestans* were much larger than in domiciliary areas and increased steadily over time. Undetected peridomestic foci were probably common because timed manual collections with an irritant lack sensitivity to detect low-density infestations that were revealed by matched peridomestic sensing devices (Gürtler et al., 2001b). The significant positive association between householders' collections of *T. infestans* in domiciliary areas (mostly adult bugs) and the occurrence of peridomestic bug infestations in the respective house within the same time period suggests that domiciliary invasion by adult bugs most likely originated in these peridomestic foci. Molecular, genetic, and morphometric techniques may help to differentiate residual from invasive triatomine populations and thus provide conclusive evidence regarding the source of the bugs (Borges et al., 1999; Dujardin et al., 1997).

In the absence of sylvatic foci of *T. infestans* (Canale and Carcavallo, 1985), the occurrence of isolated adult *T. infestans* may be explained by active dispersal from foci located within its flight range (Schofield et al., 1992; Schweigmann et al., 1988). A small logging operation located 1500 m from Trinidad (overlooked during the 1992 spraying campaign and detected as infested in November 1994) was the most likely source of the invading adult bugs collected by householders in nearby Pampa Pozo and Trinidad. The few houses in Villa Matilde and San Pablo, all infested and first sprayed in 1993 and 1994, were the likely source of adult *T. infestans* that invaded Mercedes houses located 1000 m farther apart. In addition, two cases of passive transport of *T. infestans* in bags and furniture from an infested logging operation in nearby San Luis into two previously uninfested houses at Mercedes and Villa Matilde were reported by householders in 1996–1997.

At baseline both communities were similar in several respects, but Amamá houses had thatched roofs more prone to harbor triatomines than Trinidad–Mercedes, whereas the latter were immersed in a more rural landscape with larger peridomestic compounds and more goats or sheep.

Amamá and Trinidad–Mercedes clearly differed in the frequency of well-plastered houses for 2–3 years after interventions, but not in p.i. rates of selective deltamethrin spraying. Local environmental conditions were seemingly stable over 1992–1997, although comparatively more houses of a better construction quality were built in Amamá, and more householders from Trinidad–Mercedes vacated their homes.

Improvement of house walls was made possible through the long-standing relationship of the research group with the community; the combination of housing modification with a blanket insecticide spraying demanded by most householders; use of local materials and householders' construction know-how; community awareness of the beneficial effects of plastering walls, and a minimum of technical assistance. This strategy efficiently increased the percentage of Amamá houses with well-plastered walls from 17 to 83% in nearly 50 days, requiring householders' cooperation and approximately three monthly salaries of construction workers at local rates. Only 18% of households that required improvement of walls did not participate at all, and these households mostly included single persons or transient occupants. This degree of community participation was similar to that obtained (65%) by a more intensive house modification program in Venezuela (Organización Panamericana de la Salud, 1998).

Nearly half (55%) of the improved walls kept a smooth surface for 3 years. Since the program did not include maintenance of wall plasters, by 1997 Amamá houses had returned to baseline values of wall surface state, whereas Trinidad–Mercedes showed almost no change at all throughout the observation period. Appropriate soil–cement mixtures would likely provide longer-lasting wall plasters than some of the mixtures tried by householders (Schofield et al., 1991; Organización Panamericana de la Salud, 1998; Rozendaal, 1997; Rotondaro et al., 1997). Interestingly, many households at Amamá built new houses or initiated repairs after 1992 in parallel with a major change of land tenure and use since 1989, and incipient availability of local jobs associated with enhanced forest exploitation. Improvement of housing conditions is expected to create a sense of self-esteem and identification (Briceño-León, 1990) that may itself promote new improvements over time, and reduce the likelihood of various ill health conditions.

The reduction of refuges available to *T. infestans* in the walls before insecticide spraying only slightly reduced domiciliary infestation and colonization rates over 3 years p.i. compared with a blanket spraying alone, probably because of the abundant alternative refuges available in thatched roofs and peridomestic structures. When domestic infestations were assessed by timed manual collections and sensor boxes (a standardized measure of infestation), well-plastered houses had slightly lower infestation or colonization rates than houses with bad or regular plasters in any time period. This result agrees with previous findings in Amamá in 1985–1992 (Gürtler et al., 1994). However, when domestic infestations were assessed by householders' bug collection, houses with well-plastered walls showed higher rates of infestation than other houses in both communities. As householders' collected mostly adults bugs, these most likely invaded from elsewhere. On speculative grounds, well-plastered walls might be a surrogate index of householders' awareness and willingness to catch and eliminate the bugs. In the presence of other suitable habitats and bug production habitats, such as thatched roofs (Cecere et al., 1998), the state of wall plaster alone did not prevent the domestic invasion by *T. infestans* but may have enhanced the chance of sighting and capturing bugs due to the existence of fewer refuges.

The reinfestation process in Amamá and nearby communities in 1992–1997 was less intense than between 1985 and 1992 (Gürtler et al., 1994). In 1985 only Amamá and a few dispersed nearby houses were sprayed similarly with deltamethrin by NCS; goat corrals and other animal enclosures distant from human habitations were not sprayed, and all surrounding rural areas were infested by *T. infestans*. The slower domiciliary reinfestation rates experienced in 1992–1995 than in 1985–1988 may be likely attributed to the combined effects of spraying all peridomestic sites as well as residual foci during or immediately after the attack phase; active surveillance with community participation, which included regular removal of the bugs captured; and the spraying coverage of the rest of Moreno Department since early 1994, which may have afforded some indirect protection. However, we believe that most of the reinfestation process was fueled by peridomestic foci from within the communities and from nearby houses, not from more distant villages.

Comparison of the results of combined triatomine control programs is made difficult because of differences among areas in vector species, environment and culture. In Venezuela, improvements of roof and walls decreased significantly domiciliary infestation rates and abundance of *Rhodnius prolixus* in a Trujillo community after nearly 5 years, but not in another community in Portuguesa State where only insecticide residual spraying was applied irregularly (Organización Panamericana de la Salud, 1998). In Paraguay, spraying of lambda-cyhalothrin was considered the most effective action in reducing domestic infestation rates of *T. infestans* after 18 months p.i. with respect to housing improvement alone or insecticide spraying alone (Rojas de Arias et al., 1999). In Bolivia, an integrated long-term control program including insecticide spraying and improvement of wall plasters, chicken and rabbits coops greatly reduced domestic and peridomestic infestations and child infection rates, but no control area was included (Alfred Cassab et al., 1999). These studies suggest that the elimination of *T. infestans* and the permanent interruption of transmission can be achieved through an integrated control program including a social development component and sustained surveillance. However, an economic analysis of the trade-off between devoting resources to improving houses versus devoting resources to more extensive spraying and surveillance should be carried out before making a policy recommendation.

Reinforced surveillance of the peridomestic environment is needed to achieve the local elimination of *T. infestans*. The use of already developed sensing devices for monitoring peridomestic reinfestation (Gürtler et al., 2001b) would contribute to early detection of *T. infestans* before new colonies are founded. Research on the optimal frequency and timing of insecticide spraying in domestic and peridomestic sites to achieve elimination in problem areas such as Santiago del Estero is still lacking. Environmental management methods aimed at reducing colonization rates and bug abundance in the peridomestic environment are greatly needed.

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