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MODELING/GIS, RISK ASSESSMENT, ECONOMIC IMPACT

Fine-Scale Predictions of Distributions of Chagas Disease Vectors in the State of Guanajuato, Mexico

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ABSTRACT One of the most daunting challenges for Chagas disease surveillance and control in Mexico is the lack of community level data on vector distributions. Although many states now have assembled representative domestic triatomine collections, only two triatomine specimens had been collected and reported previously from the state of Guanajuato. Field personnel from the state's Secretaría de Salud conducted health promotion activities in 43 of the 46 counties in the state and received donations of a total of 2,522 triatomine specimens between 1998 and 2002. All specimens were identified, and live insects examined for *Trypanosoma cruzi*. In an effort to develop fine-scale distributional data for Guanajuato, collection localities were georeferenced and ecological niches were modeled for each species by using evolutionary-computing approaches. Five species were collected: *Triatoma mexicana* (Herrich-Schaeffer), *Triatoma longipennis* (Usinger), *Triatoma pallidipennis* (Stål), *Triatoma barberi* (Usinger), and *Triatoma dimidiata* (Latreille) from 201 communities located at elevations of 870–2,200 m. Based on collection success, *T. mexicana* had the broadest dispersion, although niche mapping indicates that *T. barberi* represents the greatest risk for transmission of Chagas disease in the state. *T. dimidiata* was represented in collections by a single adult collected from one village outside the predicted area for all species. For humans, an estimated 3,755,380 individuals are at risk for vector transmission in the state, with an incidence of 3,500 new cases per year; overall seroprevalences of 2.6% indicate that 97,640 individuals are infected with *T. cruzi* at present, including 29,300 chronic cases.

KEY WORDS Chagas disease, Guanajuato, Mexico, triatomine, vector distribution

EIGHTEEN TRIATOMINE (Triatominae: Reduviidae) species have been documented as vectors of *Trypanosoma cruzi* in Mexico (Zárate and Zárate 1985, Vidal-Acosta et al. 2000). Nine of these species are considered as primary vector species (Ramsey et al. 2003), and most belong to two species complexes (*phyllosoma* and *protracta*) in the genus *Triatoma* (Lent and Wygodzinsky 1979). Multiple triatomine species are frequently found within a single region or state in Mexico. As a result, >71% of the Mexican population is at direct risk of acquiring *T. cruzi* infections from triatomines, and >96% of all *T. cruzi* transmission occurs via these vectors (Ramsey et al. 2003).

One of the most significant challenges for Chagas disease surveillance and control in Mexico is the lack of fine-scale (at the level of local communities) vector distribution data, as well as the almost complete ignorance of the disease–transmission characteristics and risk areas, both by the public health community and by at-risk populations. With improved malaria control in the country, in the last decade, "additional" operative vector control activities have focused primarily in urban environments owing to increases in classical and hemorrhagic dengue transmission. (To date, vector-borne disease control activities are budgeted *only* for malaria in the country.) Moreover, the recent decentralization of primary health care services to the state level has emphasized the need and the opportunity to review local and state health care priorities, and despite overburdened and shrinking

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Table 1. Communities where *Triatoma* spp. were collected in domestic habitats in the state of Gunajuato, 1998–2002

County	Code Cty.	Community	Code comm.	Longitude	Latitude	Altitude	*Triatoma* species
Abasolo	1	La Colonia	470	1013455	203400	1,690	*longipennis*
Abasolo	1	Abasolo	1	1013145	202700	1,710	*pallidipennis*
Acambaro	2	Acambaro	1	1004318	200153	1,860	*barberi*
Apaseo el Alto	4	Mandujano de Atepehuacan	36	1003445	202555	1,940	*barberi*
Apaseo el Alto	4	Santa Cruz de Gamboa	17	1003100	202318	2,010	*barberi*
Apaseo el Grande-	5	Ixtla tierra Blanca	19	1003520	203911	1,890	*barberi*
Apaseo el Grande-	5	Tierra Blanca	52	1003614	204141	2,070	*barberi*
Atarjea	6	Salitrillo	37	0994510	211506	1,400	*mexicana*
Atarjea	6	Charcas	7	0995138	211230	1,720	*mexicana*
Atarjea	6	El Chilarito	9	0995130	211121	1,800	*mexicana*
Atarjea	6	Piedra Gorda	17	0995208	211230	1,820	*mexicana*
Atarjea	6	La Joya	11	0995152	211643	1,920	*mexicana*
Atarjea	6	Aldama	3	0995006	211037	1,960	*mexicana*
Atarjea	6	Villa Aldama	3	0995006	211037	1,960	*mexicana*
Atarjea	6	El Apartadero	26	0995019	211247	1,980	*mexicana*
Atarjea	6	la tapona	21	0995220	211100	2,020	*mexicana*
Atarjea	6	Hacienda de Charcas	7	0995138	211230	1,720	*mexicana*
Celaya	7	Santa Teresa	177	1005126	203814	1,780	*barberi*
Celaya	7	Rincón de Tamayo	143	1004520	202518	1,790	*barberi*
Comonfort	9	Empalme Escobedo	10	1004500	204017	1,790	*barberi*
Comonfort	9	Xoconoxtle	15	1005702	204208	1,850	*barberi*
Comonfort	9	Pocitos de San Antonio	34	1005634	204308	1,900	*barberi*
Comonfort	9	Potrero	35	1003848	204530	1,910	*barberi*
Comonfort	9	Landín	18	1005422	204515	1,960	*barberi*
Comonfort	9	San Antonio de Corrales	41	1005750	204440	2,000	*barberi*
Coroneo	10	Coroneo	1	1002153	201151	2,270	*barberi*
Cuer⅓maro	12	San Gregorio	26	1013740	203245	1,700	*longipennis*
Cuer⅓maro	12	San Gregorio	26	1013740	203245	1,700	*pallidipennis*
Dolores Hidalgo	14	Dolores Hidalgo	1	1005558	210918	1,920	*barberi*
Dolores Hidalgo	14	Cieneguilla	57	1005615	210423	1,950	*barberi*
Dolores Hidalgo	14	La Trinidad	351	1005924	210851	1,970	*barberi*
Dolores Hidalgo	14	La Joya	140	1004226	210707	1,980	*barberi*
Dolores Hidalgo	14	Ojo Zarco	186	1005155	210143	1,980	*barberi*
Dolores Hidalgo	14	San Isidro Durazno	400	1005646	210336	1,980	*barberi*
Dolores Hidalgo	14	Santiaguillo	315	1005859	210052	1,980	*barberi*
Dolores Hidalgo	14	Palacio de Abajo	191	1005912	210120	2,000	*barberi*
Dolores Hidalgo	14	Río Azul	254	1010210	210815	2,000	*barberi*
Dolores Hidalgo	14	Los Ju⅓rez	141	1010138	211119	2,030	*barberi*
Dolores Hidalgo	14	San Isidro el Sisote	285	1010117	210506	2,040	*barberi*
Dolores Hidalgo	14	Los Quijotes	236	1010415	211004	2,050	*barberi*
Dolores Hidalgo	14	Terrero de Trancas	343	1010242	211037	2,050	*barberi*
Dolores Hidalgo	14	Pereas de Arriba	192	1010152	210100	2,060	*barberi*
Dolores Hidalgo	14	Santa B⅓rbara	306	1010035	210254	2,060	*barberi*
Dolores Hidalgo	14	Refugio de Trancas	249	1010410	211121	2,070	*barberi*
Dolores Hidalgo	14	Silleros	322	1010037	210420	2,120	*barberi*
Dolores Hidalgo	14	Tequisquiapan	340	1004912	210447	1,970	*mexicana*
Huanímaro	16	La Tinaja	26	1012830	202320	1,790	*pallidipennis*
Huanímaro	16	La Tinaja	26	1012830	202320	1,790	*longipennis*
Irapuato	17	la caja	61	1012615	204240	1,710	*barberi*
Irapuato	17	san josé de Cano	148	1012406	203820	1,720	*barberi*
Irapuato	17	Irapuato	1	1012052	204023	1,730	*barberi*
Irapuato	17	Serrano	167	1012343	204640	1,740	*barberi*
Irapuato	17	La Caja	61	1012615	204240	1,710	*longipennis*
Irapuato	17	El Coecillo	72	1012426	203757	1,720	*longipennis*
Irapuato	17	Gpe. De Rivera	93	1012808	203621	1,720	*longipennis*
Irapuato	17	san josé de Cano	148	1012406	203820	1,720	*longipennis*
Irapuato	17	Irapuato	1	1012052	204023	1,730	*longipennis*
Irapuato	17	San Luis Janamo	761	1012615	203407	1,730	*pallidipennis*
Juventino Rosas	35	Juventino	1	1005943	203832	1,750	*barberi*
Juventino Rosas	35	mesa de acosta	33	1010433	204453	1,970	*barberi*
Juventino Rosas	35	La Tinaja	80	1010218	204215	2,000	*barberi*
Juventino Rosas	35	San José del Sauz	63	1005901	204027	1,800	*barberi*
Jaral del Progreso	18	Cerrito de Camargo	4	1010233	202505	1,720	*barberi*
León	20	Ejido de los López	1121	1013448	210224	1,800	*longipennis*
León	20	Plan De Ayala	401	1014316	210421	1,770	*mexicana*
León	20	Ejido de los López	1121	1013448	210224	1,800	*mexicana*
León	20	La Cantera	1103	1013204	210436	1,860	*mexicana*
Manuel Doblado	8	Ciudad M. Doblado	1	1015658	204338	1,720	*barberi*
Manuel Doblado	8	Atotonilquillo	4	1015425	203835	1,730	*barberi*
Manuel Doblado	8	El Tecu⅓n	146	1015152	204935	1,730	*barberi*
Manuel Doblado	8	Rancho Nuevo Atotonilquillo	95	1015345	204030	1,740	*barberi*
Manuel Doblado	8	Cerrito de santiago	22	1015509	203854	1,740	*barberi*

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Table 1. (Continued)

County	Code Cty.	Community	Code comm.	Longitude	Latitude	Altitude	*Triatoma* species
Manuel Doblado	8	Frias	39	1015950	204750	1,740	*barberi*
Manuel Doblado	8	Zapote de Adjuntas	166	1015100	204007	1,750	*barberi*
Manuel Doblado	8	capulin chico	17	1014700	204010	1,760	*barberi*
Manuel Doblado	8	San Juan de la Puerta	124	1014245	204345	1,710	*longipennis*
Manuel Doblado	8	Ciudad M. Doblado	1	1015658	204338	1,720	*longipennis*
Manuel Doblado	8	Atotonilquillo	4	1015425	203835	1,730	*longipennis*
Manuel Doblado	8	Camargo de Adjuntas	2	1015035	204025	1,730	*longipennis*
Manuel Doblado	8	El Tecu⅓n	146	1015152	204935	1,730	*longipennis*
Manuel Doblado	8	Cerrito de santiago	22	1015509	203854	1,740	*longipennis*
Manuel Doblado	8	Carrizo de Godinez	19	1014945	204045	1,750	*longipennis*
Manuel Doblado	8	Zapote de Adjuntas	166	1015100	204007	1,750	*longipennis*
Manuel Doblado	8	El Varal	468	1014828	204948	1,800	*longipennis*
Manuel Doblado	8	Piedra Parada	75	1014827	204445	1,810	*longipennis*
Manuel Doblado	8	La Soledad de Leones	141	1015521	203608	1,880	*longipennis*
Manuel Doblado	8	San Antonio de la presa	110	1015653	203830	1,790	*pallidipennis*
Manuel Doblado	8	Cerrito de santiago	22	1015509	203854	1,740	*pallidipennis*
Manuel Doblado	8	El Varal	468	1014828	204948	1,800	*pallidipennis*
Manuel Doblado	8	Frias	39	1015950	204750	1,740	*pallidipennis*
Manuel Doblado	8	San Pablo	130	1014922	204503	1,730	*pallidipennis*
Manuel Doblado	8	Vado de Zapién	162	1014905	204052	1,730	*pallidipennis*
Manuel Doblado	8	Zapote de Adjuntas	166	1015100	204007	1,750	*pallidipennis*
Moroleón	21	El Salto	18	1011100	200256	1,970	*barberi*
Moroleón	21	Moroleón	1	1011125	200743	1,810	*barberi*
Pénjamo	23	Sauz de Méndez	305	1015718	202910	1,700	*barberi*
Pénjamo	23	Pénjamo	1	1014321	202548	1,770	*barberi*
Pénjamo	23	El Sauz	306	1015503	202853	1,800	*barberi*
Pénjamo	23	Huerta Grande	423	1015353	202837	1,850	*barberi*
Pénjamo	23	Mezquite de Luna	177	1015334	201747	1,690	*longipennis*
Pénjamo	23	Ordeña de Barajas	194	1014028	202050	1,700	*longipennis*
Pénjamo	23	Purísima	235	1014555	201238	1,710	*longipennis*
Pénjamo	23	Pénjamo	1	1014321	202548	1,770	*longipennis*
Pénjamo	23	Magallanes	167	1014150	202746	1,820	*longipennis*
Pénjamo	23	Zapote de Cestao	344	1014035	202900	1,820	*longipennis*
Pueblo Nuevo	24	Pueblo Nuevo	1	1012225	203133	1,700	*longipennis*
Pueblo Nuevo	24	Villa de Guadalupe	15	1012256	203356	1,720	*pallidipennis*
Romita	26	Santa Rosa de Rivas	74	1013211	204653	1,740	*longipennis*
Salamanca	27	La Capilla	42	1011800	203320	1,700	*barberi*
Salamanca	27	La Ordeña	99	1010706	204122	1,810	*barberi*
Salamanca	27	El Estanco	67	1010945	204519	1,830	*barberi*
Salamanca	27	La Joyita de Villafaña	79	1010818	204740	1,990	*barberi*
San Felipe	30	Peñuelas	163	1011505	211725	2130	*barberi*
San Felipe	30	El Aro	13	1012151	211000	2,150	*barberi*
San Felipe	30	San Vicente	254	1012029	211404	2,150	*barberi*
San Luis de la Paz	33	Las Teresas	223	1001708	213510	1,400	*barberi*
San Luis de la Paz	33	El Realito	165	1001330	213613	1,060	*mexicana*
San Luis de la Paz	33	El Guamúchil	69	1001524	213711	1,100	*mexicana*
San Luis de la Paz	33	Paso de Mezquites	512	1001420	213616	1,200	*mexicana*
San Luis de la Paz	33	Huizaches	73	1001715	213424	1,260	*mexicana*
San Luis de la Paz	33	El higueron	72	1002224	214015	1,300	*mexicana*
San Luis de la Paz	33	El Bramador	415	1001808	213608	1,340	*mexicana*
San Luis de la Paz	33	El Capadero	249	1001605	213603	1,400	*mexicana*
San Luis de la Paz	33	Las Teresas	223	1001708	213510	1,400	*mexicana*
San Luis de la Paz	33	Ojo de Agua	364	1001713	213453	1,400	*mexicana*
San Luis de la Paz	33	Mesa de la Estacada	102	1001820	213350	1,460	*mexicana*
San Luis de la Paz	33	El Saucillo	323	1001658	213654	1,480	*mexicana*
San Luis de la Paz	33	El Aguacate	484	1001958	213955	1,500	*mexicana*
San Luis de la Paz	33	Mesita de Camaron	293	1001950	214031	1,540	*mexicana*
San Luis de la Paz	33	Cañada del Potrero	19	1002429	213949	1,600	*mexicana*
San Luis de la Paz	33	Rincón del Pitayo	775	1001531	213103	1,620	*mexicana*
San Luis de la Paz	33	La Soledad	218	1004015	211110	1,980	*mexicana*
San Luis de la Paz	33	Las Adjuntas	2	1003223	212745	2,050	*mexicana*
San Luis de la Paz	33	El potrero del Sauz	325	1002547	212018	2,100	*mexicana*
San Luis de la Paz	33	San Luis de la Paz	1	1003100	211751	2,100	*mexicana*
San Luis de la Paz	33	Ejido de Ortega	119	1002416	211625	2,200	*mexicana*
San Miguel Allende	3	Banda	18	1004919	205750	1,850	*mexicana*
San Miguel Allende	3	Cienega de Juana Ruiz	64	1005203	205410	1,860	*mexicana*
San Miguel Allende	3	Corral de Piedras	77	1003536	205835	2,060	*mexicana*
San Miguel Allende	3	El Kiwi	512	1003907	205302	2,060	*mexicana*
Santa Catarina	34	Llano Blanco	19	1000328	210826	1,560	*barberi*
Santa Catarina	34	El Zapote	47	1000602	210954	1,600	*dimidiata*
Santa Catarina	34	Cruz de Diego	11	1000207	210759	1,540	*mexicana*
Santa Catarina	34	Ortega	21	1000116	210744	1,540	*mexicana*
Santa Catarina	34	Tres Alamos	34	1000201	210816	1,550	*mexicana*

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Table 1. (Continued)

County	Code Cty.	Community	Code comm.	Longitude	Latitude	Altitude	*Triatoma* species
Santa Catarina	34	Las Limitas	18	1000308	210818	1,560	*mexicana*
Santa Catarina	34	Llano Blanco	19	1000328	210826	1,560	*mexicana*
Santa Catarina	34	Santa Catarina	1	1000406	210820	1,560	*mexicana*
Santa Catarina	34	Agua Buena	2	1000401	210844	1,570	*mexicana*
Santa Catarina	34	El Tablón	32	1000441	210803	1,570	*mexicana*
Santa Catarina	34	Barrio de Santa Cruz	27	1000447	210748	1,580	*mexicana*
Santa Catarina	34	Peña Colorada	23	1000431	210904	1,590	*mexicana*
Santa Catarina	34	Charco del Muerto	13	1000607	210748	1,600	*mexicana*
Santa Catarina	34	El Mezquital	41	1000341	210757	1,600	*mexicana*
Santa Catarina	34	El Zapote	47	1000602	210954	1,600	*mexicana*
Santa Catarina	34	La Cantera	6	1000524	210705	1,630	*mexicana*
Santa Catarina	34	Corral Blanco	9	1000632	211020	1,640	*mexicana*
Santa Catarina	34	La Rusia	24	1000428	210613	1,670	*mexicana*
Santa Catarina	34	El Chapin	12	1000359	210532	1,700	*mexicana*
Santa Catarina	34	San Jose del Chilar	26	1000221	210951	1,800	*mexicana*
Santa Catarina	34	San José del Chilar	26	1000221	210951	1,800	*mexicana*
Santa Catarina	34	El Nogal	20	1000548	211157	1,850	*mexicana*
Santa Catarina	34	Paredes	22	1000528	211252	2,150	*mexicana*
Santa Catarina	34	La Faja	44	1000400	210803	1,570	*mexicana*
Santa Catarina	34	Los Juan Diegos	16	1000318	210812	1,550	*mexicana*
Silao	37	Silao	1	1012537	205633	1,780	*barberi*
Silao	37	Bajío de Bonillas	6	1012944	205654	1,790	*barberi*
Silao	37	Chichimequillas	31	1012634	210215	1,850	*barberi*
Sn. Fco. Del Rincón	31	El Refugio	113	1014448	205010	1,850	*longipennis*
Sn. Fco. Del Rincón	31	El Refugio	113	1014448	205010	1,850	*pallidipennis*
Tarimoro	39	Tarimoro	1	1004530	201715	1,770	*barberi*
Tarimoro	39	Huapango	19	1004105	202150	2,150	*barberi*
Tierra Blanca	40	Monte Prieto	28	1000810	210635	1,680	*barberi*
Tierra Blanca	40	Las Moras	29	1000948	210423	1,750	*barberi*
Tierra Blanca	40	El Guadalupe	18	1001103	210332	1,850	*barberi*
Tierra Blanca	40	Cano de San Isidro	57	1001335	210350	1,870	*barberi*
Tierra Blanca	40	Cerro Colorado	9	1001355	210610	1,890	*barberi*
Tierra Blanca	40	Cuesta de Peñones	11	1001358	210502	1,900	*barberi*
Tierra Blanca	40	Milpa Blanca	27	1000826	210453	1,900	*barberi*
Tierra Blanca	40	Rincón del Cano	38	1001429	210323	1,900	*barberi*
Tierra Blanca	40	Peña Blanca	33	1000802	210752	1,640	*mexicana*
Tierra Blanca	40	El Tepetate	44	1000921	210651	1,680	*mexicana*
Tierra Blanca	40	Fracción de Guadalupe	16	1000911	210738	1,680	*mexicana*
Tierra Blanca	40	Monte Prieto	28	1000810	210635	1,680	*mexicana*
Tierra Blanca	40	Don Blas	13	1000914	210625	1,700	*mexicana*
Tierra Blanca	40	Tierra Blanca	1	1000929	210600	1,700	*mexicana*
Tierra Blanca	40	El Mezquite	25	1000749	210601	1,730	*mexicana*
Tierra Blanca	40	Villa Unión	63	1000941	210441	1,740	*mexicana*
Tierra Blanca	40	Cieneguilla	10	1001101	210448	1,750	*mexicana*
Tierra Blanca	40	Las Moras	29	1000948	210423	1,750	*mexicana*
Tierra Blanca	40	El Salto	40	1000912	210327	1,760	*mexicana*
Tierra Blanca	40	El Zapote	64	1000942	210510	1,760	*mexicana*
Tierra Blanca	40	Torrecitas	47	1001200	210454	1,770	*mexicana*
Tierra Blanca	40	Juanica	56	1001042	210414	1,780	*mexicana*
Tierra Blanca	40	El Picacho	35	1001124	210421	1,800	*mexicana*
Tierra Blanca	40	El Progreso	87	1001108	210432	1,800	*mexicana*
Tierra Blanca	40	El Guadalupe	18	1001103	210332	1,850	*mexicana*
Tierra Blanca	40	El Sauz	42	1000840	210214	1,850	*mexicana*
Tierra Blanca	40	fraccón del Cano	6	1001349	210402	1,850	*mexicana*
Tierra Blanca	40	El Sauz del Salto	42	1000840	210214	1,850	*mexicana*
Tierra Blanca	40	Las Adjuntas	2	1001043	210212	1,860	*mexicana*
Tierra Blanca	40	Cano de San Isidro	57	1001335	210350	1,870	*mexicana*
Tierra Blanca	40	Cerro Colorado	9	1001355	210610	1,890	*mexicana*
Tierra Blanca	40	Cuesta de Peñones	11	1001358	210502	1,900	*mexicana*
Tierra Blanca	40	Milpa Blanca	27	1000826	210453	1,900	*mexicana*
Tierra Blanca	40	Rincón del Cano	38	1001429	210323	1,900	*mexicana*
Tierra Blanca	40	La Estancia	15	1000829	210046	1,950	*mexicana*
Tierra Blanca	40	La Mesita	24	1000858	205924	2,090	*mexicana*
Tierra Blanca	40	El Apartadero	53	1000819	205918	2,160	*mexicana*
Tierra Blanca	40	Peña blanca dos	34	1001057	210508	1,750	*mexicana*
Tierra Blanca	40	El Sauz del Salto	42	1000840	210214	1,850	*mexicana*
Tierra Blanca	40	Rincon del Cano	38	1001429	210323	1,900	*mexicana*
Tierra Blanca	40	Cerro colorado	9	1001355	210610	1,890	*mexicana*
Uriangato	41	El Charco	10	1010737	200846	1,950	*barberi*
Uriangato	41	El Cerro	5	1011211	200223	2,060	*barberi*
Uriangato	41	Lagunilla del Rico	16	1010524	200531	2,120	*barberi*
Valle de Santiago	42	La Barquilla	5	1012625	202005	1,700	*barberi*
Valle de Santiago	42	Salitre de Adjuntas	90	1012635	201905	1,710	*barberi*

Continued on next page

Table 1. (Continued)

County	Code Cty.	Community	Code comm.	Longitude	Latitude	Altitude	*Triatoma* species
Valle de Santiago	42	Valle de Santiago	1	1011130	202330	1,720	*barberi*
Valle de Santiago	42	Potrerillo de Torres	69	1011042	201538	1,730	*barberi*
Valle de Santiago	42	Las Jícamas	43	1012130	201638	1,850	*barberi*
Valle de Santiago	42	Mesa de san Agustín	54	1011725	202014	1,850	*barberi*
Valle de Santiago	42	Cerro Blanco	14	1011802	201825	2,060	*barberi*
Valle de Santiago	42	Armadillo	4	1011333	201700	2,080	*barberi*
Valle de Santiago	42	La Barquilla	5	1012625	202005	1,700	*longipennis*
Victoria	43	Calera	12	1001708	211209	1,950	*mexicana*
Victoria	43	Cerrito Colorado	105	1001020	211323	1,770	*barberi*
Victoria	43	El Refugio	71	1001820	211245	1,900	*barberi*
Victoria	43	Milpillas	46	1001434	212040	2,140	*barberi*
Victoria	43	Los Tres pasos		1000957	213108	1,020	*mexicana*
Victoria	43	Agua Fría	3	1001044	213046	1,040	*mexicana*
Victoria	43	El Tepehuaje	85	1000843	213144	1,060	*mexicana*
Victoria	43	Terrón Blanco	87	1001228	213732	1,100	*mexicana*
Victoria	43	Alamos de Mtz.	7	1001024	213606	1,100	*mexicana*
Victoria	43	San Antonio de la Cueva	78	1001247	212620	1,200	*mexicana*
Victoria	43	Buenavista de Guadalupe	11	1000550	213408	1,300	*mexicana*
Victoria	43	Cieneguilla	108	1001628	211451	1,340	*mexicana*
Victoria	43	Potrerillos	64	1001131	212554	1,400	*mexicana*
Victoria	43	Los Colorados	140	1000702	212907	1,420	*mexicana*
Victoria	43	El Chilcuague	24	1001149	212402	1,560	*mexicana*
Victoria	43	El Quelite	69	1000921	211120	1,700	*mexicana*
Victoria	43	La Salitrera	76	1000841	211104	1,700	*mexicana*
Victoria	43	Las Negritas	150	1001655	212400	1,700	*mexicana*
Victoria	43	Milpillas de Santiago	45	1001044	211159	1,720	*mexicana*
Victoria	43	Victoria	1	1001253	211240	1,740	*mexicana*
Victoria	43	El Carrizal de Higueras	215	1001242	211153	1,750	*mexicana*
Victoria	43	El Tepetate	179	1001045	211245	1,750	*mexicana*
Victoria	43	Las Higueras	215	1001242	211153	1,750	*mexicana*
Victoria	43	El Tasajillo	84	1001131	211238	1,750	*mexicana*
Victoria	43	Cerrito Colorado	105	1001020	211323	1,770	*mexicana*
Victoria	43	Cerro Grande	72	1001156	211100	1,770	*mexicana*
Victoria	43	Los Remedios	72	1001156	211100	1,770	*mexicana*
Victoria	43	Rancho Viejo	72	1001156	211100	1,770	*mexicana*
Victoria	43	Jacalasuchil	95	1001240	211126	1,790	*mexicana*
Victoria	43	Misión de Arnedo	48	1001505	211348	1,790	*mexicana*
Victoria	43	Corralillos	32	1001149	211009	1,820	*mexicana*
Victoria	43	Corralillos	22	1001149	211009	1,820	*mexicana*
Victoria	43	La Simona	82	1001548	211615	1,860	*mexicana*
Victoria	43	Corral de Piedras	21	1001431	211221	1,870	*mexicana*
Victoria	43	Hda. De Higueras	304	1001022	211525	1,880	*mexicana*
Victoria	43	Negritas	53	1001758	211327	1,890	*mexicana*
Victoria	43	El Refugio	71	1001820	211245	1,900	*mexicana*
Victoria	43	Sombrerete	83	1001654	211622	1,900	*mexicana*
Victoria	43	Panales	58	1001501	211535	1,920	*mexicana*
victoria	43	La Estancia	28	1001340	211546	1,940	*mexicana*
Victoria	43	El Carrizo	17	1000928	211438	1,950	*mexicana*
Victoria	43	Loma de los Chilitos	35	1001834	211741	1,960	*mexicana*
Victoria	43	Nogal Chico	54	1001544	211737	1,960	*mexicana*
Victoria	43	El Sauz de Arriba	80	1001740	211750	2,000	*mexicana*
Victoria	43	La Gavia Chica	29	1001824	211757	2,000	*mexicana*
Victoria	43	Capilla Blanca	15	1001952	211307	2,010	*mexicana*
Victoria	43	Milpillas	46	1001434	212040	2,140	*mexicana*
Victoria	43	Los Remedios	72	1001156	211100	1,770	*barberi*
Xichú	45	Ojo de Agua	62	0994746	212652	1,400	*mexicana*
Xichú	45	Los Cocos	68	0994917	212458	900	*mexicana*
Xichú	45	El Platanal	42	0995124	212615	1,020	*mexicana*
Xichú	45	La Pila	39	0995949	212641	1,100	*mexicana*
Xichú	45	Piedras Pintadas	38	0995552	211600	1,160	*mexicana*
Xichú	45	Palomas	36	0995105	212238	1,240	*mexicana*
Xichú	45	Paso de Guillermo	37	995530	211317	1,380	*mexicana*
Xichú	45	Llano Grande	22	1000440	211521	2,040	*mexicana*
Xichú	45	Piedras Pintadas	38	0995552	211600	1,160	*barberi*
Xichú	45	Paso de Guillermo	37	995530	211317	1,380	*barberi*
Xichú	45	Noria del Maltrato	31	995629	212120	880	*mexicana*
Xichú	45	Llanetes	21	995739	212058	900	*mexicana*
Xichú	45	La Majada	69	994920	212534	950	*mexicana*
Xichú	45	La Escondida	67	0995950	213105	1,070	*mexicana*
Xichú	45	San Diego de los Pitayos	49	995752	211655	1,080	*mexicana*
Xichú	45	Adjuntas	2	1000135	212025	1,100	*mexicana*

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Table 1. (Continued)

County	Code Cty.	Community	Code comm.	Longitude	Latitude	Altitude	*Triatoma* species
Xichú	45	La Salitrera	48	0995503	211622	1,200	*mexicana*
Xichú	45	Los Potrerillos	77	0995838	211622	1,200	*mexicana*
Xichú	45	El Roblar	64	0994813	212625	1,300	*mexicana*
Xichú	45	Xichú	1	1000320	211755	1,300	*mexicana*
Xichú	45	La Cieneguita	13	0995708	211433	1,340	*mexicana*
Xichú	45	Mision de Sta. Rosa	30	1000511	211713	1,560	*mexicana*
Xichú	45	Agua Zarca	5	0995520	211758	1,600	*mexicana*
Yuriria	46	San Pablo Casacuar⅓n	79	1010230	201200	1,740	*barberi*
Yuriria	46	San José Otonguitiro	71	1011458	201131	1,740	*barberi*
Yuriria	46	Juan Lucas	27	1011823	201051	1,740	*barberi*
Yuriria	46	Yuriria	1	1010740	201240	1,740	*barberi*
Yuriria	46	San Andrés Calera	61	1012300	200932	1,860	*barberi*
Yuriria	46	Tejocote de Calera	86	1012346	201048	1,900	*barberi*
Yuriria	46	Tinaja del Coyote	92	1010225	200658	1,970	*barberi*
Yuriria	46	Tejocote de Pastores	87	1010338	200650	2,010	*barberi*
Yuriria	46	Timbinal	91	1010250	200535	2,030	*barberi*
Yuriria	46	El Salteador	60	1010436	200820	2,040	*barberi*
Yuriria	46	Providencia de Calera	49	1012325	201100	2,050	*barberi*

Reference codes are from INEGI databases are included for each registry.

health budgets, conduct diagnostic analyses of Chagas disease burden. Many states now recognize their Chagas disease problems, and the need to develop cost-effective and integrated surveillance and control strategies, and so are attempting to complete preliminary risk assessments.

The first collection of triatomines in the state of Guanajuato, in central Mexico, was reported in 1956 by Biagi (Biagi 1956), for *Triatoma pallidipennis* (Stål) from Acambaro, Acambaro county. The only other previous report for triatomines was of *Triatoma barberi* (Usinger) from Los Galvanes, San Miguel de Allende county (Salazar-Schettino et al. 1983). Two seroepidemiological studies have been conducted in the state: the first, in 1991, at San José de La Presa, Purísima del Rincón county, found 6.1% of 228 samples from open population positive for antibodies to *T. cruzi* (Juarez-Leyva, personal communication). More recently, in 2000, in 60 communities in 12 counties, a seroprevalence of 2.6% ($n = 1730$) was found (López-Cárdenas, personal communication).

The current study represents a first effort to identify the principal domestic triatomine species across the entire state of Guanajuato. To provide a landscape-level view, without limitations imposed by sampling and completeness of inventory for the state, we use ecological niche modeling via evolutionary computing approaches. We then stratify Chagas transmission risk based on vector species distributions.

Materials and Methods

Study Site: Guanajuato State. Guanajuato is located in central Mexico in the high plains, with a total land area of 30,461 km^2, corresponding to 1.5% of the country's total land mass. The northern half of the state lies within the Central Mesa region; the southern half in the Transverse Volcanic Belt; and the northeast corner touches the Sierra Madre Oriental. The state has three principal climatic zones: semidry, temperate, and semihot, with an average of 800 mm of rainfall concentrated between June and September. The state holds 46 administrative counties, four major urban centers (León, Irapuato, Salamanca, and Celaya, INEGI 2000), and eight Sanitary Jurisdictions for the Primary Health Care System.

Population Sampling. Communities from 43 of the 46 counties in Guanajuato were visited repeatedly (at least one visit per year and three visits per year in 12% of the counties) between October 1998 and July 2002 for Chagas disease prevention activities. All communities visited by health promotion personnel (≈37% of all state communities), mobile medical units (Sanitary Jurisdictions 2 and 8), or the infant nutrition program PROGRESA were included in the study's activities. Health promotion personnel and vector technicians conducted community meetings, in which the population was given information regarding the disease and its vectors, bug recognition, and was requested to collect bugs observed in homes. Samples collected by the community (with name of family, date, habitat, community, and county) were sent to the Sanitary Jurisdiction (SJ) headquarters, and transported for analysis to the State Public Health Laboratory (León). Owing to the state's dispersed population, vector personnel from the SJ2 had greater contact directly with small isolated rural communities, and therefore they were able to survey a greater proportion of communities in the counties of Xichú, Victoria, and Sta. Catarina.

Analysis of Bug Collections and Entomological Indices. Data for all samples received by the State Public Health Laboratory were registered in a database. Bugs were identified using a standard key (Lent and Wygodzinsky 1979). Samples received live were examined for *T. cruzi* by direct observation of fecal samples in a standard light microscope. Standard entomological indices, including dispersion indices (number of positive villages per total villages examined × 100), were calculated for communities and counties.

Ecological Niche Modeling. Our use of ecological niche modeling, which followed on several previous tests and prototypes (Peterson 2001, Beard et al. 2002, Costa et al. 2002, Peterson et al. 2002), introduces a new feature to the technique: the use of multitemporal, remotely sensed environmental data sets as a surrogate for climatic data (Rogers 2000, Egbert et al. 2002, Hay et al. 2002, Rogers et al. 2002). This environmental data set permits fine-scale predictions across landscapes for which climatic monitoring stations are too sparse to permit development of fine-scale climate maps.

Preliminary ecological niche models were based on unique occurrence records for all species encountered in the state, by using all known existing collection records (i.e., not part of the Guanajuato state sampling program described above) from 1948 to 2002 for the area within 250 km of Guanajuato. Three members of the *phyllosoma* species group and one from the *protracta* complex had sufficient unique occurrence localities (>30 records) for analysis. All occurrence points were georeferenced to the nearest 0.1′ of latitude and longitude via reference to Mexican census information (www.conabio.gob.mx, www.inegi.gob.mx). The Guanajuato state health survey was reserved as an independent test and validation of model predictivity.

Ecological niches were modeled using the Genetic Algorithm for Rule-set Prediction (GARP) (Stockwell and Noble 1992, Stockwell 1999, Stockwell and Peters 1999), an evolutionary-computing software package available for public download. In general, the procedure focuses on modeling ecological niches (the conjunction of ecological conditions within which a species is able to maintain populations without immigration) (Grinnell 1917). Specifically, GARP relates ecological characteristics of known occurrence points to those of points randomly sampled from the rest of the study region, seeking to develop a series of decision rules that best summarize those factors associated with the species' presence (Peterson et al. 2002a). In GARP, input occurrence points are divided randomly and evenly into training and (intrinsic) testing data sets. GARP works in an iterative process of rule selection, evaluation, testing, and incorporation or rejection: a method is chosen from a set of possibilities (e.g., logistic regression, bioclimatic rules), applied to the training data, and a rule is developed or evolved. Predictive accuracy is then evaluated based on 1,250 points resampled from the intrinsic test data and 1,250 points sampled randomly from the study region as a whole. Rules may evolve by a number of means that mimic DNA evolution: point mutations, deletions, and crossing over. The change in predictive accuracy from one iteration to the next is used to evaluate whether a particular rule should be incorporated into the model, and the algorithm runs either 1000 iterations or until convergence.

We used four data layers summarizing aspects of topography (elevation, slope, aspect, and topographic index [tendency to pool water]) from the U.S. Geological Survey's Hydro-1K data set, and 12 data layers summarizing monthly composite normalized difference vegetation index values ("greenness index") drawn from the Advanced Very High Resolution Radiometer satellite. Both data sets have a native spatial resolution of ≈1 km and were resolved to the same 1-km grid across the region of study. GARP's predictive abilities have been tested and proven under diverse circumstances (Peterson et al. 1999, 2001, 2002c; Peterson 2001; Anderson et al. 2002, 2003).

To take advantage of the random-walk nature of the GARP algorithm, we developed 100 replicate models of each species' ecological niche. We used the procedures described in Anderson et al. (2003) for choosing a "best subset" of the 100 models, based on optimal combinations of error statistics. The procedure is based on the observations that 1) models vary in quality, 2) variation among models involves an inverse relationship between error of omission (leaving out true distributional area) and commission (including areas not actually inhabited), and 3) best models (as judged by experts blind to error statistics) are clustered in a region of minimum omission of independent test points and moderate area predicted (an axis related directly to commission error). The relative position of the cloud of points relative to the two error axes provides an assessment of the relative accuracy of each model. To choose best subsets of models, we 1) eliminated all models that had omission error >5% based on independent intrinsic test points, 2) calculated the median area predicted present among these zero-omission points, 3) identified the 10 models closest to the overall median area predicted, and 4) summed these best subsets models.

Projection of the rule-sets for these best subsets models onto geography provided distributional predictions for species' ranges. Model quality was tested and validated via the independent Guanajuato state triatomine survey data. χ^2 tests were used to compare observed success in predicting distributions of test points with those expected under random models (proportional area predicted present provides an estimate of occurrence points correctly predicted were the prediction to be random with respect to the distribution of the test points). Predicted presence was defined as the area in which all best-subsets models agreed in prediction of presence.

Disease Prevalence and Burden. Based on the areas identified by the ecological niche models at different levels of model agreement, human settlements in the state were ranked from lowest (1) to highest (10) for vector transmission risk. Three strata were defined based on this ranking: 1–3, low risk; 4–7, medium risk; and 8–10, high risk. Community, demographic, and housing information from the 2000 National Census (INEGI 2000) were combined with the risk statistics, and total population at risk, seropositive population, incidence, mortality, and disease burden were calculated by county based on an overall

Table 2. Communities collecting triatomines in Guanajuato counties; stratification of at-risk communities based on species collected and altitude ranges for each species in the state

County	Triatomines present				No. comm. at-risk	Comm. with health promotion	Comm. infested	Collect success (%)
	800–1,200 masl	1,200–1,700 masl	1,700–1,900 masl	1,900–2,270 masl				
1			l,p		301	204	2	1.0
2			b	b	213	80	1	1.3
3			m	m	471	161	4	2.5
4			b	b	122	52	2	3.8
5		b	b	b	142	57	2	3.5
6	m	m	m	m	36	14	11	81.5
7			b	b	263	113	2	1.8
8			b, l, p	b	304	67	26	38.9
9			b	b	150	54	6	11.1
10		b	b	b	10	6	1	17.6
11			b	b	109	53		
12			l, p		89	12	1	8.4
13				m, b	74	35		
14			m, b	m, b	526	73	18	24.6
15			b	b	129	13		
16			l, p		38	22	2	9.2
17			b, l, p	b	472	191	10	5.2
18		b	b		38	19	1	5.1
19				b	136	48		
20	m	m	m, l	m	509	240	4	1.7
21			b	b	20	9	1	10.8
22				b	73	54		
23			b, l	b	482	184	12	6.5
24			l, p		52	28	2	7.0
25			b, l, p		106	46		
26			l		257	70	1	1.4
27			b	b	309	156	4	2.6
28			b	b	75	47		
29				b	190	44		
30		b	b	b	307	87	3	3.5
31			l, p		192	86	1	1.2
32				m, b	193	109		
33	m	m, b	m, b	m, b	440	143	22	15.4
34		m, b, d	m, b,	m, b	41	26	26	100.0
35			b	b	155	60	4	6.6
36			b	b	14	6		
37			b	b	385	72	3	4.2
38			b	b	26	10		
39			b	b	76	50	2	4.0
40			m, b	m, b	48	37	37	100.0
41		b	b	b	32	15	4	26.6
42		b	b, l	b	231	28	9	32.4
43	m	m, b	m, b	m, b	158	47	47	100.0
44			b	b	120	80		
45	m	m, b	m, b	m, b	76	22	22	100.0
46			b	b	106	44	11	25.3
Total					6284	3073	247	

amsl, above mean sea level; comm, community; b, *T. barberi;* d, *T. dimidiata;* l, *T. longipennis;* m, *T. mexicana;* p, *T. pallidipennis.*

seroprevalence of 2.6% (López-Cárdenas, personal communication).

Results

Among the 43 counties surveyed, after nearly 4 yr of Chagas vector promotion activities, 32 (74%; 201 communities) reported collections of bugs, representing 3.9% of all communities potentially at risk (Table 1). In total, 2,522 triatomine specimens of five species were collected: *T. barberi*, *T. pallidipennis, Triatoma longipennis* (Usinger), *Triatoma mexicana* (Herrich-Schaeffer), and *Triatoma dimidata* (Latreille) (one adult only). In 14% of communities contributing bugs, more than one species of triatomine was found. The species most commonly found sympatric were 1) *T. barberi*, *T. longipennis*, and *T. pallidipennis* (three communities, one county); 2) *T. barberi* and *T. mexicana* (14 communities, five counties), 3) *T. longipennis* and *T. pallidipennis* (four communities, four counties), and 4) *T. barberi* and *T. longipennis* (seven communities, four counties).

Health promotion activities, mobile medical units, and/or vector control activities of the primary healthcare system covered an average of 37% of communities in the 43 counties (Table 2). Using altitudinal range, proportion of communities included in health promo-

Table 3. Dispersion of domestic triatomines in at-risk communities in Guanajuato, 1998–2002

Species	At-risk communities with health promotion (*n*)	Communities positive for bugs (*n*)	Counties positive for bugs (*n*)	Dispersion index (%)
T. barberi	2,192	95	26	4.3
T. longipennis	1,177	13	6	1.1
T. pallidipennis	656	31	12	4.7
T. mexicana	907	171	9	18.9

tion activities, and vector species detected to stratify at-risk communities, a broad range of collection success was observed in each county (0.4–77.1%), either reflecting real variation in dispersion indices or differences in community participation from county to county. There was a general tendency for higher "potential" dispersion indices (>10%) only where *T. mexicana* or *T. barberi* were present, in the counties of Atarjea, Santa Catarina, Tierra Blanca, Victoria, and Xichú. Using estimated numbers of communities at risk where promotion activities were conducted, dispersion indices for the four triatomine species were 4.3, 1.1, 4.7, and 18.9% for *T. barberi, T. longipennis, T. pallidipennis,* and *T. mexicana,* respectively (Table 3).

Bug collection sites inside and outside houses are reported in Table 4. *T. barberi* inside houses was found equally in bedrooms (23%) and walls (24%) and proportionally few from floors or ceilings; in the peridomicile, a high proportion (33%) of collections was from animal corrals. Although few collections of *T. longipennis* and *T. pallidipennis* were from the intradomicile, greatest proportions of specimens were found in bedrooms (36 and 55%, respectively), with fewer from walls (4 and 27%, respectively), and even fewer from floors or ceilings. *T. mexicana* was found predominately on walls (56%), followed by bedrooms (25%); in the peridomicile, only 2% of samples were collected from animal corrals.

Due to often lengthy transport of bugs to the State Laboratory, not all specimens arrived in adequate condition for fecal examinations. Only 1,207 (47.9%) of the total 2,522 specimens collected were examined for presence of *Trypanosoma cruzi* (Table 5). Few specimens of *T. longipennis* and *T. pallidipennis* were collected, although 45.5 and 7.7%, respectively, of these were positive. From a total of 163 *T. barberi* and 1,009 *T. mexicana*, 19.0 and 2.9%, respectively, were positive for *T. cruzi.*

Only one adult specimen of *T. dimidiata* was collected over the 4 yr, which may indicate the transport of an isolated specimen rather than domestic infestation. In addition to domestic specimens, only *T. longipennis* and *T. mexicana* were collected along rural roads in sylvan areas surrounding communities.

Ecological Niche and Transmission Risk Areas. All triatomine occurrence data points within 250 km of Guanajuato from a database that includes all registries (published or from state health authorities, but not including the survey described herein) of triatomine collections in Mexico from 1948 to present were modeled, and niche models were developed for all five species occurring in the state, although sample sizes were insufficient for *T. dimidiata.* Overlaying the independent Guanajuato state health survey data, the correspondence between prediction and independent test data were extremely good and highly statistically significant for *T. longipennis* ($\chi^2 = 34.7$, $P = 3.78 \times 10^{-9}$), *T. pallidipennis* ($\chi^2 = 16.4$, $P = 5.24 \times 10^{-5}$), and *T. mexicana* ($\chi^2 = 63.2$, $P = 1.86 \times 10^{-15}$), and significant if less close for *T. barberi* ($\chi^2 = 6.3$, $P = 0.012$). The only occurrence of *T. dimidiata* detected in the Guanajuato state health data set was not predicted as habitable for the species based on the ecological niche models.

Finally, the Guanajuato state health data set and the national data set were combined, and ecological niche model prediction maps generated for the four species confirmed to infest domestic habitats in the state (Figs. 1–4). Overall, Guanajuato has 8978 communities with more than two houses registered; 8,589 of these communities are predicted to have some risk of infestation by triatomine vectors, and hence vector transmission of Chagas disease (Table 6). Of the 8,589 communities at risk, 8,383 have "high" risk for infestation by at least one triatomine species. The species representing the greatest overall risk in terms of number of communities potentially inhabited are *T. barberi* and *T. mexicana.*

Using the highest risk prediction score from any of the four principal triatomine species, we estimate that 80.5% or 3,755,375 inhabitants of Guanajuato are at direct risk for vector transmission among the total population of 4,665,000 (Table 6) and that 99.2% of this population is at "high" risk. Based on this latter at-risk

Table 4. Triatomine domestic collection sites inside and outside houses

Species	Intradomicile						Peridomicile	
	Bedroom	Floor	Wall	Roof	Kitchen	Other	Animal corral	Patio/garden
T. barberi	29	4	30	4	7	50*	9	18
T. longipennis	9	3	1	1	2	9	1	5
T. pallidipennis	6	0	3	0	0	2	1	1
T. mexicana	96	21	216	3	7	43*	1	62

Other includes sites inside houses, e.g., corridors, bathrooms, and living room.
[a] 32 for *T. barberi* and 36 for *T. mexicana* were broadly registered as 'intradomicile.'

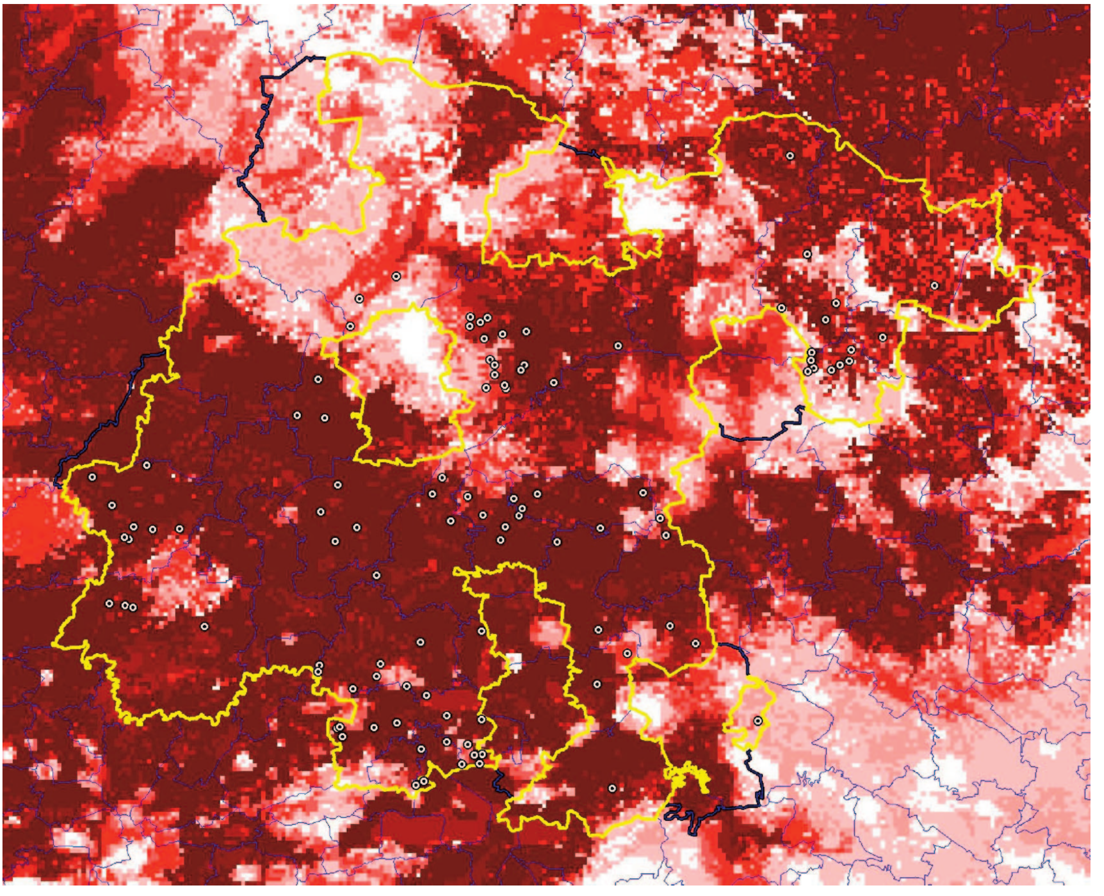

Fig. 1. Niche prediction area for *T. barberi* in the state of Guanajuato. Highest risk is indicated in dark red and lowest in white; collection sites are marked by open circles in the map.

population to calculate overall prevalence, and given a recent serological survey that found a seroprevalence of 2.6% for anti-*T. cruzi* antibody in the state, an estimated 97,640 inhabitants have Chagas disease in the state, of which 29,293 would currently be in the chronic phase (30% of all cases). Incidence for Chagas cases is estimated as 3,485 per year, in the absence of any vector control measures. With 29,293 current chronic cases, we estimate that the state and/or the population spends an average U.S.$20,505,100 in treatment alone, independent of whether the cases are recognized as Chagas, or as "cardiac insufficiency," where most of the current cases in Mexico are classified.

Table 5. Infection of triatomines with *T. cruzi*

Species	Examined	Positive *T. cruzi*	*T. cruzi* infection (%)
T. barberi	163	31	19.0
T. longipennis	22	10	45.5
T. pallidipennis	13	1	7.7
T. mexicana	1009	29	2.9

Discussion

Four triatomine vector species of Chagas disease have now been identified and their distributions modeled in the state of Guanajuato: *T. barberi*, *T. longipennis*, *T. mexicana*, and *T. pallidipennis*. All of these species are well adapted to domestic habitats, with colonization both inside and outside houses, and their *T. cruzi* transmission potential verified, with infection rates lowest for *T. mexicana* (6%) and highest for *T. longipennis* (46%). Despite collection bias, a result of more intensive health promotion and survey activities in *T. mexicana*-infested communities (highest collection success), this species has similar albeit slightly lower potential risk compared with *T. barberi* by using niche modeling. Both species are the most widely dispersed triatomines within the state and may infest all communities in certain counties. Neither *T. longipennis* nor *T. pallidipennis* were collected from >10% of communities within given counties. These preliminary data will require verification through entomological surveys by using standardized methods and trained vector technicians.

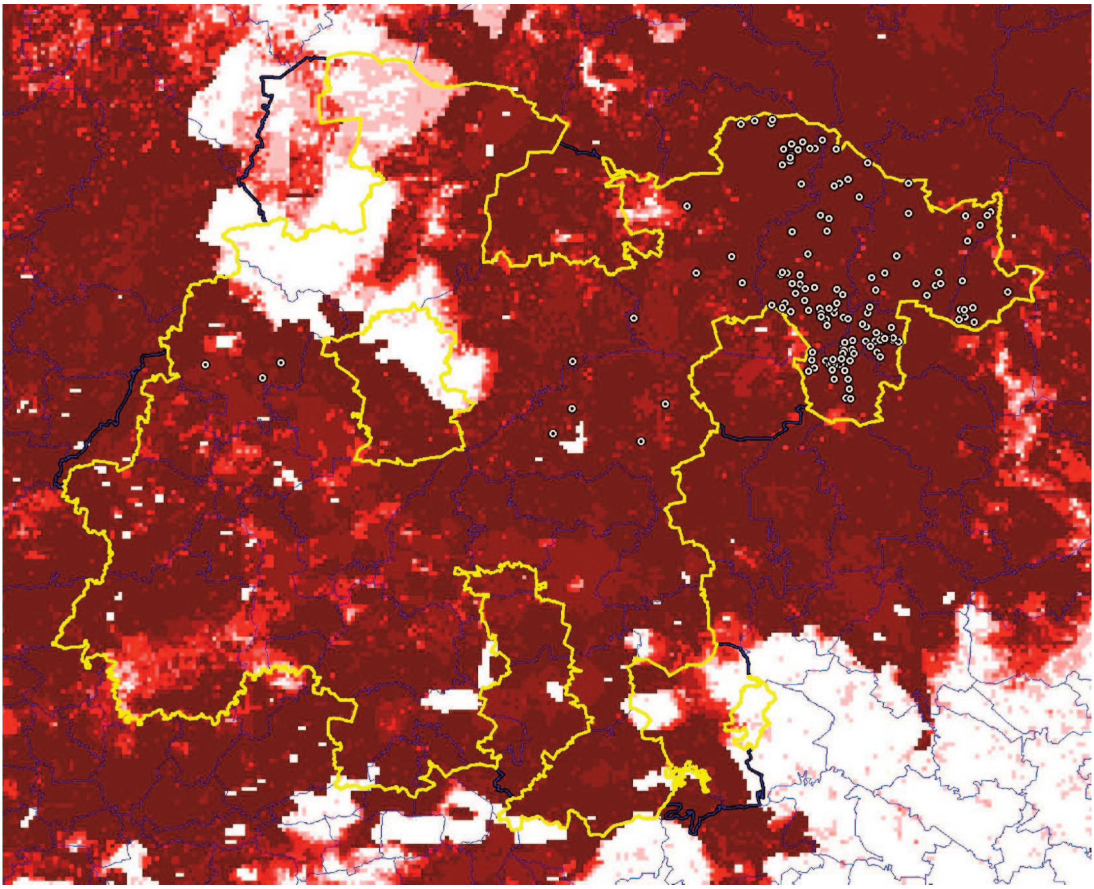

Fig. 2. Niche prediction area for *T. mexicana* in the state of Guanajuato. Highest risk is indicated in dark red and lowest in white; collection sites are marked by open circles in the map.

Most Mexican states are currently attempting to determine the distributions of their triatomine vectors to define at-risk populations for Chagas disease transmission (Ramsey et al. 2003) and to evaluate requirements for surveillance and control programs. This task is daunting, given the extent of the territory, and the lack of funds and personnel with which to conduct such surveys—indeed, it is clear that without local assistance and without more accessible methodology to measure vector distributions, diagnosis of the situation will remain obscure. This study succeeded in initiating a long-needed awareness program within the state for triatomines and Chagas disease, as well as intensive collection of vectors by local residents and vector-borne disease technicians. Nevertheless, it is clear that these collections must be supervised and supplemented with specific entomological surveys, at least in the initial stages of a surveillance program.

This study also presents a powerful example of the role that ecological niche modeling can play in this challenge (Peterson et al. 2002b). Niche-based predictions for species' distributions can be powerful tools with which health care services can outline vector species' distributional areas, establish potential disease transmission risk areas, and determine real versus potential infestation. In our analysis, triatomine collection data from states within 250 km of Guanajuato coincided precisely with the local residents' collection data, and ecological niche models developed from the two data sets were virtually identical. In other words, using just the existing data from *outside* the state, we predicted the triatomine distributions with accuracy, thereby obviating the need for preliminary surveys. Such predictions could be used to design and guide on-ground survey efforts, thereby focusing effort considerably, and reducing costs significantly. These models can then be refined via secondary surveys conducted by trained technicians in sentinel counties, so that specific entomological indicators can be evaluated.

The case of the single individual of *T. dimidiata* collected is an important example of the potential use of ecological niche models to define risk. Using data sets from states surrounding Guanajuato, we conclude that this species has virtually no potential distributional area within the state. Collection of a lone adult

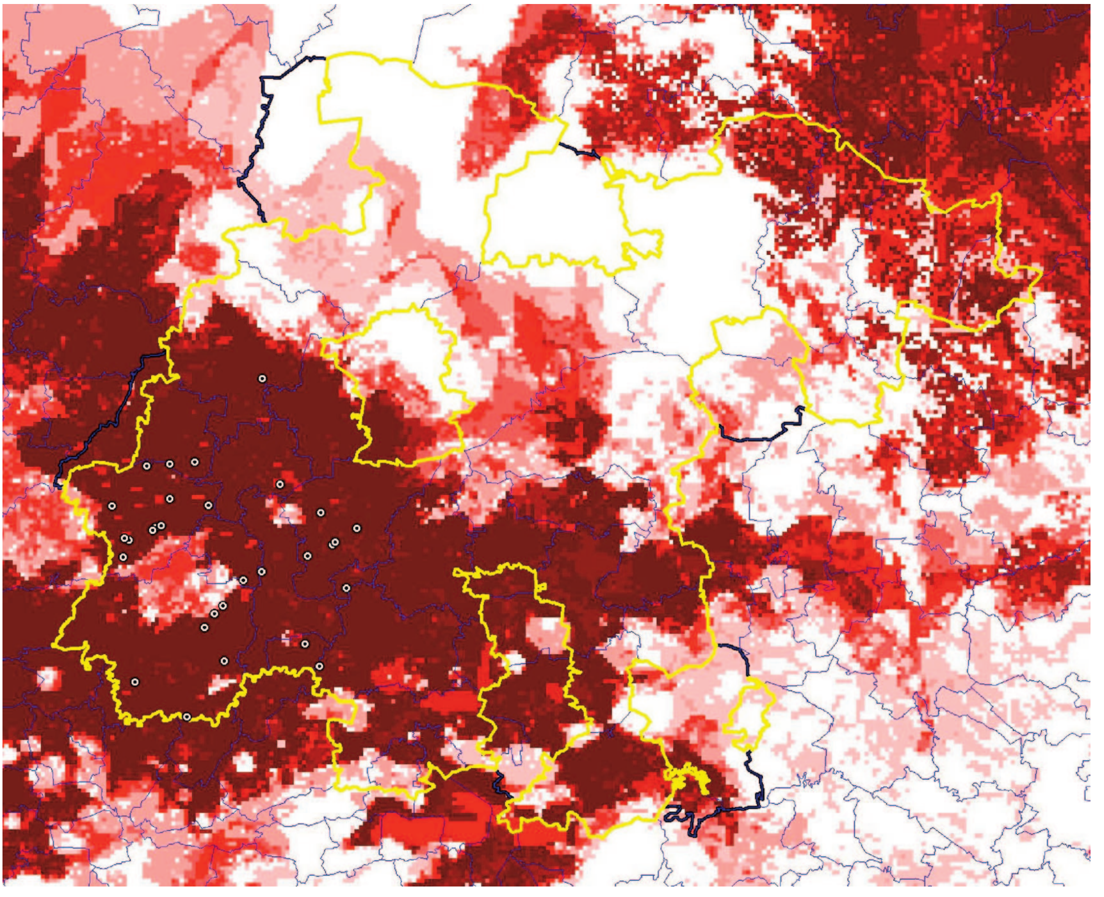

Fig. 3. Niche prediction area for *T. longipennis* in the state of Guanajuato. Highest risk is indicated in dark red and lowest in white; collection sites are marked by open circles in the map.

specimen can therefore be considered spurious, probably the result of human-assisted transport. Nevertheless, the lack of potential niche areas suggests that even though this species is transported periodically to the state, it probably cannot establish in sylvan habitats.

Chagas disease transmission risk is a function of the presence of triatomines in domestic habitats, which in turn is dependent on the presence of triatomines in surrounding sylvan areas. Niche modeling provides the only tool available to date for defining potential dispersion of individual triatomine species and hence potential transmission risk.

The use of prediction models for Chagas surveillance programs is currently feasible at both local and statewide levels. Control programs can use these models to determine at-risk populations, to monitor control program activities and to allow control strategies to be stratified according to real or potential risk (Ramsey et al. 2003). Potential infestation areas will require specific surveillance activities, different from actual infestation areas, and information processing from population-based collections or specific entomological surveys can feed the models so that they can accurately and rapidly track program needs. Most importantly, as demonstrated in this study, they can identify preliminary risk areas so that vector control technicians can direct their surveys cost-effectively for more precise and local infestation indicators.

Table 6. Predicted risk (high, score 15–20; medium, score 8–14; low, score 1–7) for vector transmission for all communities in Guanajuato by using GARP, and stratified by vector species

Species	High (%)	Medium (%)	Low (%)	Total
T. barberi	8,299 (96.9)	221 (2.6)	41 (0.5)	8,561
T. longipennis	5,132 (72.9)	601 (8.5)	1,307 (18.6)	7,040
T. pallidipennis	5,272 (65.9)	800 (10.0)	1,922 (24.1)	7,994
T. mexicana	7,504 (88.9)	497 (5.9)	436 (5.2)	8,437

Note that sympatry and niche overlap among species results in repetition of at-risk communities.

Acknowledgments

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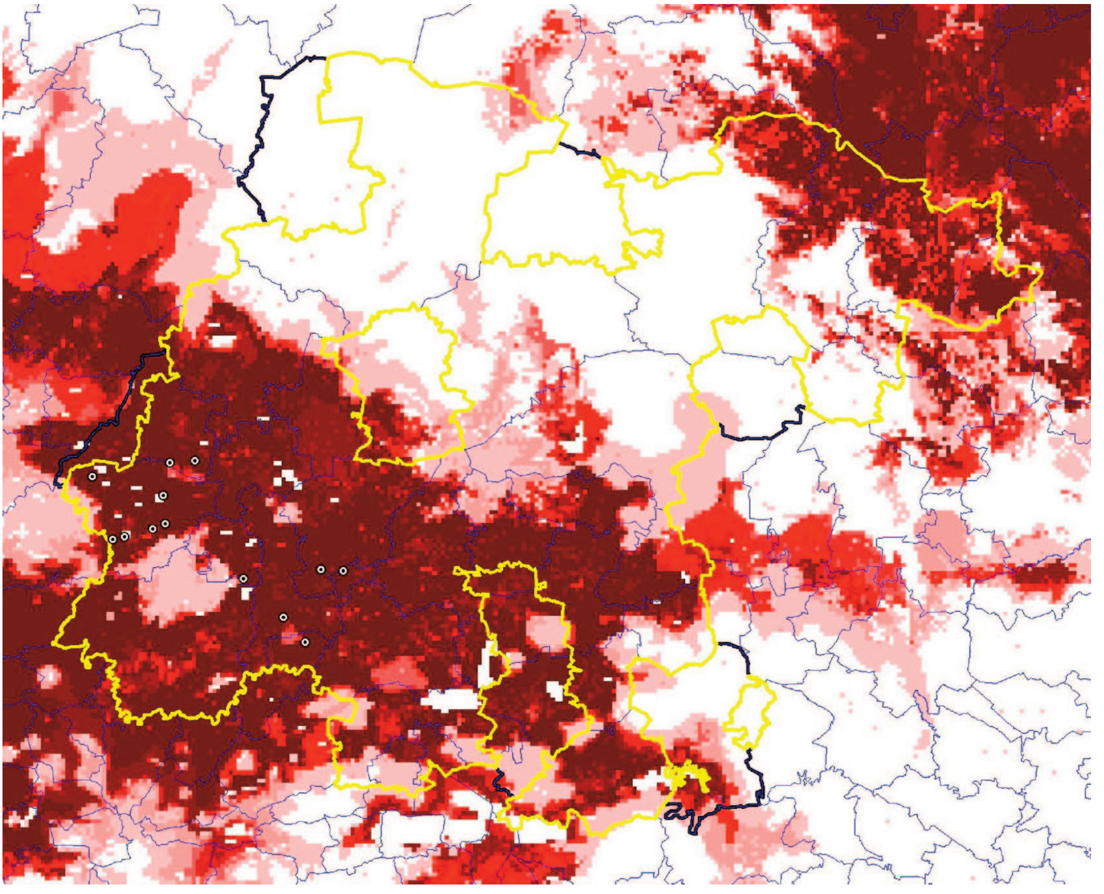

Fig. 4. Niche prediction area for *T. pallidipennis* in the state of Guanajuato. Highest risk is indicated in dark red and lowest in white; collection sites are marked by open circles in the map.

juato, especially the state and Sanitary Jurisdiction epidemiologists and technical personnel from the vector control program. We thank Vianey Vidal from the National Laboratory for Diagnosis and Epidemiological Reference for assistance with quality control of taxonomic identifications and Gely Peña Arguntia for dedication in health promotion and county collection activities. We also thank the Vector Control Coordinators from the states of Mexico, Morelos, San Luis Potosi, and Veracruz for provision of data regarding *Triatoma* distributions not reported in the scientific literature and to the Comisión Nacional para la Conservación y Uso de la Biodiverisdad (CONABIO) for access to mammal distributional data. This study was financed through the Guanajuato State Health budget, federal project funds from the National Institute of Public Health Mexico to J.M.R., and by the U.S. National Science Foundation and Consejo Nacional para Ciencia y Tecnología to A.T.P.

References Cited

Anderson, R. P., M. Laverde, and A. T. Peterson. 2002. Geographical distributions of spiny pocket mice in South America: insights from predictive models. Global Ecol. Biogeogr 11: 131–141.

Anderson, R. P., D. Lew, and A. T. Peterson. 2003. Using intermodel variation in error components to select best subsets of ecological niche models. Ecol. Model. 162: 211–232.

Beard, C. B., G. Pye, F. J. Steurer, Y. Salinas, R. Campman, A. T. Peterson, J. M. Ramsey, R. A. Wirtz, and L. E. Robinson. 2002. Chagas disease in a domestic transmission cycle in southern Texas, USA. Emerg. Infect. Dis. 9: 103–105.

Biagi, F. 1956. Nueva Infección natural con *Schizotrypanum cruzi.* Variabilidad cromática y otras notas sobre triatomas Mexicanas. Prensa Med. Mex 21: 123–126.

Costa, J., A. T. Peterson, and C. B. Beard. 2002. Ecological niche modeling and differentiation of populations of *Triatoma brasiliensis* Neiva, 1911, the most important Chagas disease vector in northeastern Brazil (Hemiptera, Reduviidae, Triatominae). Am. J. Trop. Med. Hyg. 67: 516–520.

Egbert, S. L., E. Martinez-Meyer, M. A. Ortega-Herta, and A. T. Peterson. 2002. Use of datasets derived from time-series AVHRR imagery as surrogates for land cover maps in predicting species' distributions. Proceedings IEEE 2002. Int. Geo. Rem. Sen. Symp. (IGARSS) 4: 2337–2339.

Grinnell, J. 1917. Field tests of theories concerning distributional control. Am. Nat. 51: 115–128.

Hay, S. I., M. F. Myers, N. Maynard, and D. J. Rogers. 2002. From remote sensing to relevant sensing in human health. Photogrammetric Eng. Remote Sensing 68: 109–111.

Lent, H., and P. Wygodzinsky. 1979. Revision of the Triatominae (Hemiptera: Reduviidae), and their significance as vectors of Chagas disease. Bull. Amer. Mus. Nat. Hist. 163: 520.

López-Cárdenas, J. 2001. Identificación y distribución espacial de las especies de vectores de la enfermedad de Chagas en el Estado de Guanajuato, de 1998–2000. M.S. thesis, Universidad de Guanajuato, León, Guanajuato, México.

Peterson, A. T. 2001. Predicting species' geographic distributions based on ecological niche modeling. Condor 103: 599–605.

Peterson, A. T., and D. A. Vieglais. 2001. Predicting species invasions using ecological niche modeling. BioScience 51: 363–371.

Peterson, A. T., J. Soberon, and V. Sanchez-Cordero. 1999. Conservatism of ecological niches in evolutionary time. Science (Wash. DC) 285: 1265–1267.

Peterson, A. T., V. Sanchez-Cordero, J. Soberon, J. Bartley, R. H. Buddemeier, and A. G. Navarro-Siguenza. 2001. Effects of global climate change on geographic distributions of Mexican Cracidae. Ecol. Model. 144: 21–30.

Peterson, A. T., M. A. Ortega-Huerta, J. Bartley, V. Sanchez-Cordero, J. Soberon, R. H. Buddemeier, and D.R.B. Stockwell. 2002a. Future projections for Mexican faunas under global climate change scenarios. Nature (Lond.) 416: 626–629.

Peterson, A. T., V. Sanchez-Cordero, C. B. Beard, and J. M. Ramsey. 2002b. Ecologic niche modeling and potential reservoirs for Chagas disease, Mexico. Emerg. Infect. Dis. 8: 662–667.

Peterson, A. T., D.R.B. Stockwell, and D. A. Kluza. 2002c. Distributional prediction based on ecological niche modeling of primary occurrence data, pp. 617–623. *In* J. M. Scott [ed.], Predicting species occurrences: Issues of scale and accuracy. Island Press, Washington, DC.

Peterson, A. T., D. A. Vieglais, and J. Andreasen. 2005. .Migratory birds as critical transport vectors for West Nile Virus in North America. Emerg. Inf. Dis. (in press).

Ramsey, J. M., R. Ordoñez, A. Tello Lopez, J. L. Pohls, V. Sanchez-Cordero, and A. T. Peterson. 2003. Actualidades sobre la epidemiología de la enfermedad de Chagas en México, pp. 85–105. *In* J. M. Ramsey, A. Tello Lopez, and J. L. Pohls [eds.], Iniciativa para la vigilancia y control de la enfermedad de Chagas en México. Instituto Nacional de Salud Pública, México.

Rogers, D. J. 2000. Satellites, space, time and the African trypanosomiases, pp. 130–171. *In* S. I. Hay, S. Randolph, and D. J. Rogers [eds.], Remote sensing and GIS in public health. Academic, New York.

Rogers, D. J., S. E. Randolph, R. W. Snow, and S. I. Hay. 2002. Satellite imagery in the study and forecast of malaria. Nature (Lond.) 415: 710–715.

Salazar-Schettino, P. M., I de Haro, J. Jiménez, and E. Garcia Carrera. 1983. Dos nuevas localidades de transmisores de la enfermedad de Chagras en la República Mexicana. Salud Pública Méx. 25: 77–82.

Stockwell, D.R.B. 1999. Genetic algorithms II, pp. 123–144. *In* A. H. Fielding [ed.], Machine learning methods for ecological applications. Kluwer Academic Publishers, Boston, MA.

Stockwell, D.R.B., and I. R. Noble. 1992. Induction of sets of rules from animal distribution data: a robust and informative method of analysis. Math. Comp. Simul. 33: 385–390.

Stockwell, D.R.B., and D. P. Peters. 1999. The GARP modelling system: problems and solutions to automated spatial prediction. Int. J. Geogr. Inf. Sys. 13: 143–158.

Vidal-Acosta, V., S. Ibáñez-Bernal, and C. Martínez-Campos. 2000. Infección Natural de chinches Triatominae con *Trypanosoma cruzi* asociadas a la vivienda humana en México. Salud Pública de Mex. 42: 496–503.

Zárate, L. G., and R. J. Zárate. 1985. A checklist of the Triatominae (Hemiptera: Reduvidae). Int. J. Entomol. 27: 102–127.

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