

Anaplasma phagocytophilum Infection in Small Mammal Hosts of *Ixodes* Ticks, Western United States

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A total of 2,121 small mammals in California were assessed for *Anaplasma phagocytophilum* from 2006 through 2008. Odds ratios were >1 for 4 sciurids species and dusky-footed woodrats. High seroprevalence was observed in northern sites. Ten tick species were identified. Heavily infested rodent species included meadow voles, woodrats, deer mice, and redwood chipmunks.

Anaplasma phagocytophilum is a tick-transmitted pathogen that causes granulocytic anaplasmosis in humans, horses, and dogs (1–3). *A. phagocytophilum* is maintained in rodent-*Ixodes* spp. tick cycles, including the western black-legged tick (*Indopacetus pacificus*) in the western United States (4). Transovarial transmission does not occur, and *I. pacificus* feeds only 1 time per stage, so infection must be acquired by a juvenile tick feeding on an infected mammal. Suggested reservoirs in the West include the dusky-footed woodrat (*Neotoma fuscipes*), for which chronic infection has been observed, and the western gray squirrel (*Sciurus griseus*), which are frequently infected in nature (5,6). The northern coast range and Sierra Nevada foothills of California (4,7), where abundant rodents include deer mice (*Peromyscus* spp.), woodrats, and chipmunks (*Tamias* spp.), have moderate to high levels of granulocytic anaplasmosis. We sought to evaluate granulocytic anaplasmosis exposure and infection and describe the *Ixodes* spp. tick fauna in small mammals from central and northern coastal California.

The Study

Small mammals were caught in live traps (HB Sherman, Tallahassee, FL, USA, and Tomahawk Live Trap,

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DOI: 10.3201/eid1407.071599

Tomahawk, WI, USA) at 9 sites or collected as carcasses on roads (online Technical Appendix, available from www.cdc.gov/EID/content/14/7/1147-Techapp.pdf) from 2006 to 2008. Traps were set at locations of observed active rodent use or dens and baited with peanut butter and oats or corn, oats, and barley. Rodents were anesthetized with ketamine and xylazine delivered subcutaneously, examined for ectoparasites, and bled by retro-orbital abrasion or femoral venipuncture. The blood was anticoagulated with EDTA. Shrew (*Sorex* spp.) carcasses were retrieved when found in traps, kept cold, and then sampled in the laboratory. Live shrews were examined for ticks but released without further processing. All carcasses were identified to species, age, and sex; examined for ectoparasites; and then dissected for coagulated heart blood and spleen. Ectoparasites were preserved in 70% ethanol for identification. Data were included for animals from 3 previous studies (5,8,9).

Plasma anti-*A. phagocytophilum* immunoglobulin G (Ig) was assayed by an indirect immunofluorescent antibody assay (3), by using *A. phagocytophilum*-infected HL-60 cells as substrate and fluorescein isothiocyanate-labeled goat anti-rat heavy and light chain IgG (Kirkegaard and Perry, Gaithersburg, MD, USA). This assay does not distinguish exposure to *A. phagocytophilum* from *A. platys*, but the PCR was specific for *A. phagocytophilum*. PCR was performed for all flying (*Glaucomys sabrinus*), Douglas (*Tamiasciurus douglasii*), and gray squirrels; all chipmunks from Santa Cruz and Marin Counties; a random subset of chipmunks from Humboldt Redwoods State Park and Hendy Woods State Park; and a random subset of individual mammals of other species. DNA was extracted from whole blood by using a kit (DNeasy Tissue kit, QIAGEN, Valencia, CA, USA), and real-time PCR was performed as described previously (5).

Data were analyzed with “R” (www.r-project.org), with a cutoff for statistical significance of $p = 0.05$. Differences in seroprevalence among small mammal species and between sexes were assessed by χ^2 test. Individual small mammals’ risk for *A. phagocytophilum* exposure and infection were assessed as a function of sex, species, and location by calculating odds ratios (OR) and 95% confidence intervals (CI). Multivariate logistic regression was performed to evaluate seropositivity as a function of site, host species, and interactions to evaluate possible interaction and confounding between the variables.

A total of 2,121 small mammals, including 2,100 rodents, 20 shrews, and 1 lagomorph, were evaluated for exposure to and infection with *A. phagocytophilum* and infestation with *Ixodes* spp. ticks (Table 1). The overall seroprevalence was 15.2% (95% CI 13.6–16.9). Highest values and ORs >1 occurred in dusky-footed woodrats, tree squirrels, and some chipmunk species (Table 1; online Technical Appendix). The PCR prevalence among rodents

Table 1. Seroprevalence and PCR prevalence of *Anaplasma phagocytophilum* among small mammal species, northern and central coastal California*

Mammal species	<i>A. phagocytophilum</i> IFA			<i>A. phagocytophilum</i> msp2 PCR		
	Seropositive	Seroprevalence	95% CI	PCR positive	PCR prevalence	95% CI
<i>Clethrionomys californicus</i>	1	12.50	0.6–53.3	0	0	0–53.7
<i>Glaucomys sabrinus</i>	2	14.29	2.5–43.9	1	16.7	0.8–63.5
<i>Mus musculus</i>	0	0.00	0–25.3	0	0	0–34.4
<i>Microtus californicus</i>	2	5.88	1.0–21.1	0	0	0–17.8
<i>Neotoma cinerea</i>	0	0.00	0–94.5	0	0	0–94.5
<i>N. fuscipes</i>	167	50.15	44.7–55.6	8	4.3	2.0–8.6
<i>N. macrotis</i>	2	3.03	5.3–11.5	1	1.8	0.09–10.6
All <i>Neotoma</i>	169	42.25	37.4–47.3	9	3.7	1.8–7.1
<i>Peromyscus boylii</i>	3	8.82	2.3–24.8	1	4.0	0.2–22.3
<i>P. californicus</i>	2	0.67	0.1–2.7	0	0	0–3.8
<i>P. maniculatus</i>	18	3.46	2.1–5.5	0	0	0–6.6
<i>P. truei</i>	1	2.56	0.1–15.1	NT		
<i>Peromyscus</i> spp.	0	0.00	0–53.7	NT		
All <i>Peromyscus</i>	24	2.68	1.8–4.0	1	0.45	0.02–2.9
<i>Rattus rattus</i>	0	0.00	0–37	0	0	0–37.1
<i>Reithrodontomys megalotis</i>	0	0.00	0–17.2	1	6.3	0.3–32.3
<i>Spermophilus beecheyi</i>	0	0.00	0–4.2	0	0	0–20.0
<i>S. lateralis</i>	2	22.22	3.9–59.9	NT		
<i>Sciurus carolinensis</i>	11	57.89	34.0–78.9	3	18.8	5.0–46.3
<i>S. griseus</i>	34	70.83	55.7–82.6	6	15.8	6.6–31.9
<i>S. niger</i>	1	100.00	55.0–100.0	0	0	0–94.5
All <i>Sciurus</i>	46	47.83	33.1–62.9	9	16.4	8.2–29.3
<i>Sorex</i> spp.	0	0.00	0–37.0	0	0	0–94.5
<i>Sylvilagus bachmani</i>	0	0.00	0–94.5	NT		
<i>Tamias amoenus</i>	6	6.82	2.8–14.8	NT		
<i>T. merriami</i>	0	0.00	0–48.3	0	0	0–40.2
<i>T. minimus</i>	0	0.00	0–4.9	NT		
<i>T. senex</i>	5	4.81	1.8–11.4	NT		
<i>T. speciosus</i>	4	33.33	11.3–64.6	NT		
<i>T. sonomae</i>	1	14.29	0.7–58.0	2	50.0	15.0–85.0
<i>T. ochrogenys</i>	30	27.52	19.6–37.0	2	6.9	1.2–24.2
<i>Tamias</i> spp.	2	8.33	1.5–28.5	NT		
All <i>Tamias</i>	48	13.45	10.2–17.5	4	34.0	3.2–24.1
<i>Tamiasciurus douglasii</i>	6	40.00	17.5–67.1	0	0	0–60.4
Total	300	15.24	13.7–16.9	33	3.8	2.9–5.3

*IFA, immunofluorescence assay; CI, confidence interval; NT, not tested.

tested was 3.8% (N = 652, 95% CI 2.9–5.3); highest values were reported in tree squirrels and some chipmunk species (Table 1). Although deer mice have been reported to be exposed to *A. phagocytophilum* (10,11), we found little evidence of this in our study. Woodrats at northern sites tended to be infected, while sciurids (excluding ground squirrels) showed high rates of exposure at multiple sites, consistent with previous reports (5). A total of 60% of eastern gray squirrels from Connecticut were seropositive with reservoir competence documented by producing PCR-positive ticks after feeding on infected squirrels (12). A PCR-positive eastern chipmunk (*Tamias striatus*) was reported from Minnesota (13).

Location was an important determinant of exposure to infection, with high seroprevalence in the Hoopa Valley Indian Reservation and Hendy Woods State Park (Table 2). ORs significantly <1 were observed for Samuel P. Taylor State Park and the Morro Bay area, and 5 sites in the far northern coast range and Quincy in the Sierra Nevada had ORs >1 (online Technical Appendix). Statistical analy-

sis failed to document a significant interaction between site and host species, but confounding was apparent, with overrepresentation of gray squirrels and woodrats in some high prevalence sites (online Technical Appendix). PCR prevalence was high at Sutter Buttes State Park and Siskiyou County (both with low sample size) and Big Basin State Park and Hendy Woods State Park, each ≈12% (Table 2). Results are consistent with prior reports for horses and dogs (4). Previous spatial analysis documented increased *A. phagocytophilum* risk in redwood, montane hardwood, and blue oak/foothill pine habitats (14). In our dataset, obvious habitat differences would not account for differences in disease exposure, given the presence of live oak, tanoak, redwood, and Douglas fir at many sites. Further ecologic studies to identify differing ecologic factors among these sites would be useful.

Tick species observed in our study sites include possible enzootic vectors and several human-biting species, including *I. pacificus* and *I. angustus* (online Technical Appendix). Host species from which relatively large col-

Table 2. Regional seroprevalence and PCR prevalence rates for exposure to *Anaplasma phagocytophilum* in small mammals in various sites, northern and central California*

Site	<i>A. phagocytophilum</i> IFA			<i>A. phagocytophilum</i> msp2 PCR		
	Seropositive	Seroprevalence	95% CI	PCR positive	PCR prevalence	95% CI
Big Basin State Park	16	6.30	3.76–10.22	5	12.20	4.58–27.00
Humboldt Redwoods State Park	24	16.90	11.33–24.31	2	6.06	1.06–21.62
Hoopa Valley Indian Reservation	173	36.19	31.91–40.70	6	4.14	1.69–9.18
Hendy Woods State Park	43	22.51	16.93–29.22	5	12.19	4.58–27.00
King Range National Conservation Area	1	3.45	0.18–19.63	0	0.00	0.00–80.21
Mendocino County (roadside only)	0	0.00	0.00–94.53	0	0.00	0.00–94.54
Morro Bay regional communities	5	1.23	0.45–3.01	2	0.67	0.12–2.65
Placerville City region (roadside only)	1	1.00	5.46–1.00	1	1.00	5.46–1.00
Quincy City region (roadside only)	2	50.00	15.00–84.99	0	0.00	0.00–60.42
Sutter Buttes State Park	3	7.50	1.96–21.48	1	50.00	9.45–90.55
Sagehen Research Station	17	7.69	4.68–12.24	0	0.00	0.00–60.42
Siskiyou County (roadside only)	3	1.00	30.99–1.00	1	33.33	1.76–87.47
Sonoma	1	1.00	5.46–1.00	0	0.00	0.00–94.54
Samuel P. Taylor State Park	3	1.75	0.42–5.45	2	4.26	0.74–15.73
Trinity County (roadside only)	2	40.00	7.26–82.96	0	0.00	0.00–53.71
Sacramento River Valley (roadside only)	3	1.00	30.99–1.00	0	0.00	0.00–69.00
Willow Creek Town (roadside only)	3	0.30	8.09–64.63	0	0.00	0.00–60.42
Yolo County	1	6.67	0.35–33.97	0	0.00	0.00–25.35

*IFA, immunofluorescence assay; CI, confidence interval.

lections were obtained included meadow voles, woodrats, deer mice, tree squirrels, and redwood chipmunks (*T. ochrogenys*). Tick diversity was highest on redwood chipmunks and in more northerly sites (online Technical Appendix). *I. angustus*, primarily a nidicolous tick of rodents but occasionally bites humans and is a competent vector for *Borrelia burgdorferi* sensu stricto (15), occurred on most rodent species. *I. spinipalpis*, which occurred on woodrats, deer mice, squirrels, and chipmunks, functions as a primary vector for *B. bissettii* in a woodrat enzootic cycle (16), and *Neotoma mexicana* and *I. spinipalpis* have an enzootic cycle in Colorado for *A. phagocytophilum*.

Conclusions

We show that a strong distinction can be made in possible reservoir capacity among rodent species, with many, such as deer mice and voles, only contributing to the ecology of granulocytic anaplasmosis through their support of ticks but not *A. phagocytophilum* infection. Others, including tree squirrels and woodrats, are frequently infected, in addition to supporting ticks. Considerable similarities exist between the ecology of *A. phagocytophilum* and *B. burgdorferi* in the West, although the large diversity of genospecies that exists for *B. burgdorferi* has not been reported for *A. phagocytophilum*. These data provide a starting point for future work to clarify the reservoir competence of small mammals for *A. phagocytophilum* and to determine how ecologic interactions among small mammals, other vertebrate hosts, multiple possible vectors, and both *B. burgdorferi* and *A. phagocytophilum* could

affect the enzootic persistence of these pathogens and risk to humans and animals.

Acknowledgments

We thank Niki Drazenovich, Elizabeth Holmes, Bernadette Clueit, Michael Adjemian, Jamie Bettaso, Greta Wengert, and Edwin Saada for field and laboratory assistance; and Patrick Foley for suggestions for analysis. Personnel at each of the study sites (Hoopa Valley Indian Tribe, UC Reserve System, California State Parks, Bureau of Land Management, and private land owners) provided invaluable access and logistic support.

Financial support was provided by the UC Davis Center for Vectorborne Diseases and the Committee on Research.

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Technical Appendix

Table 1. Study sites evaluated for granulocytic anaplasmosis in wild rodents, northern and central coastal California

Study site	Dominant vegetation	Region	Latitude and longitude (decimal degrees)	Elevation (m)	Distance to coast (km)
Big Basin State Park	Redwood, live oak, tanoak, madrone, chaparral (1 site only)	Central coast range	37.10.621; 122.12.328	368	21
Humboldt Redwoods State Park	Redwood, Douglas fir, tanoak, madrone, live oak	Northern coast range	40.17.770; 123.59.178	610	26
Hoopa Valley Indian Reservation	Douglas fir, tanoak, madrone	Northern coast range	41.10.333; 123.56.520	109–1200	26
King Range National Conservation Area	Douglas fir, tanoak, madrone, redwood (pockets), live oak	Northern coast range	40.08.059; 124.07.404	61–610	3.9
Mendocino	peri-urban, live oak, Douglas fir	Northern coast range	39.40.050; 123.30.296	555	41
Morro Bay	Live oak, Monterey pine, eucalyptus	Central coast range	35.22.088; 120.49.464	61	1.6
Placerville	Douglas fir, Jeffrey pine, incense cedar	Sierra Nevada foothills	38.45.899; 120.49.464	1189	206
Quincy	Jeffrey pine, Douglas fir, incense cedar	Sierra Nevada	39.53.408; 120.51.312	1400	265
Sutter Buttes State Park	Blue oak, live oak,	Central valley butte	39.12.805; 121.48.167	247	151
Sagehen Research Station	Jeffrey pine, pine, red fir, white fir	Sierra Nevada	39.44.000; 120.22.000	1950	315
Siskiyou	Douglas fir, tanoak, madrone	Klamath	41.18.077; 123.32.296	198	48
Sonoma	Live oak	Northern coast range	38.19.169; 122.36.711	274	34
Samuel P. Taylor State Park	Redwood, live oak, tanoak, madrone	Northern coast range	38.01.232; 122.40.774	134	11
Trinity	Douglas fir, tanoak, madrone	Klamath	40.44.286; 123.03.222	488	131
Sacramento Valley	peri-urban	Central valley	38.33.481; 121.25.694	9	130
Willow Creek	peri-urban, Douglas fir, tanoak, madrone	Northern coast range	40.56.302; 123.37.615	229	41
Yolo	Live oak, blue oak, foothill pine	Northern coast range	38.49.382; 122.12.250	137	121

Table 2. Risk factors for *Anaplasma phagocytophilum* seropositivity with statistically significant odds ratios*

Risk factor	Odds ratio	95% CI lower	95% CI upper	p value
<i>Sciurus carolinensis</i>	14.01	3.15	62.40	5.0×10^{-4}
<i>Sciurus griseus</i>	23.43	6.19	88.66	3.5×10^{-6}
<i>Neotoma fuscipes</i>	10.38	3.11	34.65	1.4×10^{-4}
<i>Peromyscus californicus</i>	0.07	0.01	0.43	4.2×10^{-3}
<i>Tamiasciurus douglasii</i>	6.89	1.43	33.18	0.016
<i>Tamias ochrogenys</i>	3.92	1.11	13.81	0.033
Humboldt Redwoods	3.16	1.55	6.42	2.6×10^{-3}
Hoopa Valley	3.25	1.77	5.97	1.5×10^{-4}
Hendy Woods	4.37	2.28	8.36	8.3×10^{-6}
Morro Bay	0.19	0.07	0.54	1.7×10^{-3}
Quincy	29.64	2.53	347.50	6.9×10^{-3}
Samuel P. Taylor	0.28	0.08	0.98	0.047
Trinity	15.17	1.98	115.99	8.8×10^{-3}
Willow Creek	7.06	1.58	31.52	0.01

*CI, confidence interval.

Table 3. Proportion of all hosts collected from sites in northern and central California represented by *Sciurus* spp. and *Neotoma* spp.

Location	Animals tested	Tree squirrels tested	Proportion of animals that were squirrels	Woodrats tested	Proportion of animals that were woodrats
Big Basin State Park	254	21	8.3	25	9.8
Humboldt Redwoods State Park	142	5	3.5	8	5.6
Hoopa Valley Indian Reservation	478	12	2.5	273	56.1
Hendy Woods State Park	191	8	4.2	20	10.5
King Range National Conservation Area	29	1	3.4	0	0
Mendocino County (roadside only)	1	1	100.0	0	0
Morro Bay regional communities	407	0	0	40	9.8
Placerville City region (roadside only)	1	1	100.0	0	0
Quincy City region (roadside only)	6	3	50.0	0	0
Sutter Buttes State Park	40	0	0	1	2.5
Sagehen Research Station	221	0	0	1	0.4
Siskiyou County (roadside only);	4	4	100.0	0	0
Sonoma	1	0	0	1	100.0
Samuel P. Taylor State Park	171	1	0.6	21	12.3
Trinity	5	5	100.0	0	0
Sacramento Valley	3	3	100.0	0	0
Willow Creek	10	4	40.0	0	0
Yolo	15	2	13.3	13	86.7

Table 4. Tick species and stage recovered from rodents throughout California*

Host Species	<i>Dermacentor</i> sp.			<i>D. occidentalis</i>			<i>Ixodes</i> sp.			<i>I. angustus</i>			<i>I. ochotonae</i>			<i>I. pacificus</i>			<i>I. spinipalpis</i>			<i>I. woodi</i>		
	A	N	L	A	N	L	A	N	L	A	N	L	A	N	L	A	N	L	A	N	L	A	N	L
<i>C. californicus</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	
<i>G. sabrinus</i>	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	
<i>M. californicus</i>	0	0	0	0	13	8	0	0	0	2	4	0	0	0	0	0	0	1	0	0	0	0	0	
<i>M. musculus</i>	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	
<i>N. fuscipes</i>	0	1	0	0	3	0	1	3	1	3	11	0	0	10	1	1	2	3	9	2	1	3	0	
<i>P. boylii</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	
<i>P. californicus</i>	0	0	0	0	1	3	2	0	1	5	25	7	0	0	0	0	2	4	0	0	2	3	0	
<i>P. maniculatus</i>	0	2	1	0	1	7	10	0	1	3	31	5	6	0	0	7	3	20	0	0	4	2	0	
<i>P. truei</i>	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	
<i>R. rattus</i>	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	
<i>R. megalotis</i>	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>S. carolinensis</i>	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	2	0	0	0	0	0	0	0	
<i>S. griseus</i>	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	6	19	0	3	0	0	0	
<i>Sp. beecheyi</i>	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	1	0	0	0	0	0	0	
<i>T. merriami</i>	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	
<i>T. ochrogenys</i>	0	1	1	0	0	0	1	1	1	2	12	3	6	0	0	0	8	85	0	1	0	1	0	
<i>T. sonomae</i>	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	
<i>Tamiasciurus douglasii</i>	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	
<i>Sorex</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	
Total	0	5	2	0	18	19	15	4	4	17	92	19	16	1	1	10	22	139	9	6	8	9	0	

*Data not shown: 1 *I. hearlei* adult was observed on a northern flying squirrel; 3 adult *I. jellisoni* on deer mice. A = adult; N = nymph; L = larvae.

Table 5. Ticks collected on rodents from 8 different study areas in California*

Study areas	<i>Dermacentor</i> sp.			<i>D. occidentalis</i>			<i>Ixodes</i> sp.			<i>I. angustus</i>			<i>I. ochotonae</i>			<i>I. pacificus</i>			<i>I. spinipalpis</i>			Total		
	A	N	L	A	N	L	A	N	L	A	N	L	A	N	L	A	N	L	A	N	L	A	N	L
Big Basin State Park	0	0	0	0	0	0	2	0	1	0	4	1	1	0	0	6	0	1	0	0	0	12	4	3
Rural Yolo County	0	0	0	0	0	0	0	3	1	0	0	0	0	10	1	0	0	0	0	0	0	0	13	2
Humboldt	0	0	0	0	0	0	4	0	0	1	13	0	9	0	0	1	3	12	0	2	0	17	18	12
Redwoods State Park	0	3	1	0	0	0	4	3	0	2	19	3	5	0	0	1	10	97	7	1	3	21	36	104
King Range National Conservation Area	0	0	0	0	0	3	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0	0	1	5
Morro Bay regional communities	0	0	0	0	16	16	0	0	0	13	49	10	0	0	0	0	3	3	1	0	5	14	68	34
Samuel P. Taylor State Park	0	2	1	0	0	0	5	0	1	0	13	2	1	0	0	3	2	8	0	1	0	15	18	12
Sutter Buttes State Park	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1

*Data not shown: 3 *I. jellisoni* adults were recovered from Samuel P. Taylor State Park; adult *I. woodi* were collected from Big Basin State Park (3), Humboldt Redwoods State Park (2), Henny Woods State Park (2), and Samuel P. Taylor State Park (4). A = adult; N = nymph; L = larvae.