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Seasonal activity patterns of the western black-legged tick, *Ixodes pacificus*, in relation to onset of human Lyme disease in northwestern California

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ABSTRACT

Seasonal activity patterns of questing western black-legged ticks, *Ixodes pacificus* were investigated in northwestern California. Adult *I. pacificus* became active in the fall (late October/early November) and their appearance was associated with the first rain of the season. Following a peak in January, the abundance of adult ticks declined such that they were rare or absent by June/July. The nymphal tick activity season occurred from January through October, and larval activity occurred from April to June, but sometimes extended into October. Thus, potentially infectious ticks (nymphs and adults) present a year-round risk of Lyme disease transmission in northwestern California. The seasonality of Lyme disease cases in humans, based on the onset of erythema migrans, mirrored tick activity patterns and was year-round in cases infected in California. Peak incidence in humans occurs from May through July, and indicates that most disease transmission is from nymphal ticks. This study demonstrates that tick activity patterns are more extended than previously recognized in northwestern California.

Introduction

Vector-borne zoonotic diseases often are maintained in complex transmission cycles involving multiple vertebrate hosts, their arthropod vectors and environmental factors. Consequently, disease risk is a culmination of the interactions between the environment and vector, host, and pathogen populations, which can be strongly influenced by seasonal variation in any of these components. Information on the seasonal activity of vector populations allows insights into when to effectively time control measures and how to educate the public about disease risk and behaviors that might reduce exposure to vector-borne disease.

Lyme disease, caused by the spirochete *Borrelia burgdorferi*, is the most commonly reported vector-borne disease in the United States. Its signs and symptoms in humans can include a "bulls-eye" rash (erythema migrans), fever, fatigue, arthritis, carditis, and neurological manifestations (Steere, 1989; Steere et al., 2004, Bacon et al., 2008). The spirochete is transmitted by ixodid ticks which possess a three-stage life cycle: eggs that hatch into larvae, molt into nymphs and subsequently molt into adults (Gray et al., 2002, Kurtenbach et al., 2006). Larval *Ixodes* spp. are not infected transovarially with *B. burgdorferi* and thus do not transmit Lyme disease bacteria to people or animals (Rollend et al., 2013). Larval and nymphal ticks acquire *B. burgdorferi* infections when they feed on an infectious host, and transmit the infection when they feed in a subsequent life-stage, i.e., as nymphs or adults (Gray et al., 2002, Kurtenbach et al., 2006). In the northeastern and upper midwestern United States, the primary vector is the black-legged tick (*Ixodes scapularis*) whereas in California the main vector is the western black-legged tick (*I. pacificus*). *Ixodes* spp. nymphs are considered the primary life stage responsible for *B. burgdorferi* transmission to humans in North America, due to their small size and aggressive biting habits; though adult females also bite and transmit *B. burgdorferi* occasionally (Clover and Lane, 1995; Falco et al., 1999). Nymphal and adult *I. pacificus* also feed on domestic animals (cats, dogs, horses etc.) (Castro and Wright, 2007).

Seasonal patterns of tick abundance vary across the United States. For *I. scapularis* in the northeastern USA, larval activity begins and peaks in the late-summer/fall (August–September), though questing larvae are also present in the spring and early summer (Yuval and Spielman, 1990). Nymphal *I. scapularis*

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Table 1
Summary of published *Ixodes pacificus* questing patterns observed in northwestern California.

Location (county)	Date of investigation	Adult season	Peak adult abundance	Nymphal season	Peak nymphal abundance	Reference
Mendocino	Apr 1989–Mar 1990	Oct–June	Nov–May	Mar–Sep	Apr–July	Clover and Lane, 1995
Mendocino	Feb 1987–August 1988	Nov–June	March			Lane, 1990
Mendocino	Mar–Aug 1998–2001			Mar–July/Aug	Apr–June	Eisen et al., 2002
Marin, Mendocino, Humboldt, Santa Cruz	Aug 2005–May 2007	Nov–June	Dec–Feb	Feb–Oct	May–July	Rejmanek et al., 2011
Contra Costa	Dec 1990–Aug 1991	Dec–Apr/June	Dec–Mar (Jan max)			Kramer and Beesley, 1993
Contra Costa	Mar–Aug 2008			Mar–July	Mar–June	Padgett and Bonilla, 2011
Alameda, Marin	Jan–Mar/Apr 1994 and 1995	Jan-Mar		May–July		Li et al., 2000
Alameda	Jan–Aug (multiple years)	Jan–May	Jan–Apr	Apr–Aug	May–July	Hui et al., 1998

activity peaks in the summer (June–July–August) (Ostfeld et al., 1996; Falco et al., 1999; Gatewood et al., 2009). Adult *I. scapularis* are most active in fall and spring (Ostfeld et al., 1996, Falco et al., 1999). The seasonal timing of patterns of onset of human Lyme disease cases in the northeast USA reflects trends in nymphal *I. scapularis* abundance (Falco et al., 1999). However, in the upper midwest, larval activity peaks earlier in summer (June–July) and is overlapped by nymphal tick activity (peak in June–July, with continued activity through September–October) (Hamer et al., 2012). Adult *I. scapularis* are active through much of the year but abundance peaks in spring (April) and fall/early winter (October–November) (Hamer et al., 2012).

In Mendocino County, in northwestern California, *I. pacificus* larvae and nymphs begin to infest western fence lizards (*Sceloporus occidentalis*) in early spring (March), peak in April–May, decline in June, and are rare from July onwards (Eisen et al., 2001). Densities of questing *I. pacificus* nymphs manifest similar trends (Eisen et al., 2002). Most Lyme disease cases in Mendocino County (measured by the incidence of erythema migrans among patients) occur between March and August (Clover and Lane, 1995). Furthermore, the timing and magnitude of peak nymphal density varies across woodland types: more defined, higher peaks occur in warmer and drier hardwood-dominated woodlands compared with cooler and more humid redwood-dominated habitats (Eisen et al., 2003). Adult *I. pacificus* have been observed questing from October onwards, are abundant from November to May and then absent from July to September (Clover and Lane, 1995). Similar trends have been observed in other counties in northwestern California (Kramer and Beesley, 1993; Hui et al., 1998; Table 1) though descriptions of immature tick seasonal abundance patterns are largely restricted to Mendocino County.

Here we report seasonal trends of larval, nymphal, and adult *I. pacificus* abundance in several sites in northwestern California, using a combination of monitoring at consistently visited study-sites, opportunistic tick collections and existing literature. We demonstrate that tick activity patterns are more extended than previously recognized, e.g., immature ticks can be active from January through October. The seasonality of Lyme disease cases in California mirrors the extended nymphal activity pattern. We discuss the implications for *B. burgdorferi* persistence in scenarios representing *B. burgdorferi* ecology in California versus the northeastern United States.

Materials and methods

We present data gathered by members of California Department of Public Health's (CDPH) Vector-borne Disease Section (VBDS) from several different studies, as well as data garnered from opportunistic tick sampling. Unless otherwise noted, habitat at all sites was coast live oak woodland, consisting primarily of coast live oak (*Quercus agrifolia*), Pacific madrone (*Arbutus menziesii*), California bay (*Umbellularia californica*); and occasional Douglas fir (*Pseudotsuga menziesii*), and coastal redwood (*Sequoia sempervirens*). The understory was dominated by introduced grasses including wild oats (*Avena fatua*), barley (*Hordeum* spp.), rye grass (*Elymus* spp.), and brome (*Bromus* spp.). Patches of western poison-oak (*Toxicodendron diversilobum*) and native bunch grasses were also present.

Ticks were counted or collected over multiple seasons at specific locations as described below in Napa, Sonoma and Marin Counties.

Sampling for adult ticks (Napa and Sonoma Counties).

Ticks were counted visually on grass stems and other vegetation that aligned the uphill side of trails, i.e., direct observation, without removal. Surveys began in the fall (September/October), and were conducted every 1–2 weeks until two consecutive surveys failed to find any adult *I. pacificus* ticks.

Bothe-Napa Valley State Park, Napa Co. (38.5453, −122.5288; Fig. 1) was sampled from January 2002 until December 2007, along the uphill side of 188 m of trail adjacent to a perennial creek. Rainfall data were obtained from the Bothe-Napa State Park's weather station for the period 2004–2007. In Sonoma County, three sites were sampled from September (in 2002 and 2003) until June/July. One site (27 m transect) was in Fairfield Osborn Preserve (38.3407, −122.5986), owned and managed by Sonoma State University since 1997. The other two sites were in Annadel State Park (38.5479, −122.5291, transect length = 178 m; 38.4070, −122.7999, transect length = 140 m).

Sampling for adult ticks (San Mateo County)

Adult ticks were collected at Windy Hill Open Space Preserve (37.3644, −122.2451) by flagging vegetation or leaf litter with 1 m^2 white flannel flags, in chaparral and grassland habitat along 850 m of trail. Ticks were collected from January to August 2011 and from November 2011 to May 2012.

Sampling for larval and nymphal ticks (Sonoma County)

At Jack London State Park, Sonoma County (38.3432, −122.5480) larval and nymphal ticks were collected by flagging leaf litter, rocks, logs, and tree trunks with 1 m^2 white flannel flags every 2 weeks from May to early September, 2009 and from July to October, 2010. Three staff flagged 2 separate 0.405 ha areas under oak/bay canopy for 1 h each (total of 6 h of flagging per day).

Tick sampling—all life stages (Marin County)

At China Camp State Park, Marin County, (38.0056, −122.4968), ticks were collected by flagging vegetation or leaf litter with 1 m^2 white flannel flags. Leaf litter was sampled 1–2 times a month from