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Previously unrecorded damage to oak, *Quercus* spp., in southern California by the goldspotted oak borer, *Agrilus coxalis* Waterhouse (Coleoptera: Buprestidae)

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Abstract. A new and potentially devastating pest of oaks, *Quercus* spp., has been discovered in southern California. The goldspotted oak borer, *Agrilus coxalis* Waterhouse (Coleoptera: Buprestidae), colonizes the sapwood surface and phloem of the main stem and larger branches of at least three species of *Quercus* in San Diego Co., California. Larval feeding kills patches and strips of the phloem and cambium resulting in crown die back followed by mortality. In a survey of forest stand conditions at three sites in this area, 67% of the *Quercus* trees were found with external or internal evidence of *A. coxalis* attack. The literature and known distribution of *A. coxalis* are reviewed, and similarities in the behavior and impact of this species with other tree-killing *Agrilus* spp. are discussed.

Key Words. Agrilus coxalis, California, flatheaded borer, introduced species, oak mortality, *Quercus agrifolia*, *Quercus chrysolepis*, *Quercus kelloggii*, range expansion.

Introduction

Extensive mortality of coast live oak, *Quercus agrifolia* Née (Fagaceae), Engelmann oak, *Quercus engelmannii* Greene, and California black oak, *Q. kelloggii* Newb., has occurred since 2002 on the Cleveland National Forest (CNF) in San Diego Co., California. Hardwood (primarily oak) mortality was aerially mapped across 6447 ha and has impacted an estimated 17000 trees on the Descanso Ranger District of the CNF (USDA Forest Service, Pacific Southwest Region (R5), Forest Health Monitoring 2009). *Quercus* spp. mortality has also been evident on state, private, and Native American lands adjacent to the CNF. Without a clear causal agent (Bohne and Rios 2006—2008), this phenomenon of oak mortality has been known among forest health specialists and local residents as "oak croak."

Several evergreen and deciduous oaks are dominant or co-dominant canopy species in southern oak woodlands of California. *Quercus agrifolia* is commonly found below 1200 m in coastal foothills, valleys, and canyons. *Quercus engelmannii* is found inland in foothills below 1200 m. Canyon live oak, *Quercus chrysolepis* Liebm., is widely distributed in canyons, moist slopes, and flats below 2000 m. On the CNF, *Quercus kelloggii* is found further upslope (1219–1828 m) in co-dominant canopy positions with Jeffrey pine, *Pinus jeffreyi* Grev. & Balf. (Pinaceae).

Initial attempts to explain the causes of mortality among southern California oaks focused on *Phytophthora ramorum* S. Werres, A.W.A.M. de Cock & W.A. Man In't Veld, 2001, the causal agent of sudden oak death and significant tree mortality in coastal areas of northern and central California. However, no evidence of *P. ramorum* was detected at these sites (P.A. Nolan, County of San Diego, personal communication in litt.), and evidence for other pathogens, such as *Armillaria* spp. or *Phytophthora cinnamomi* Rands, 1922, was also scant (Bohne and Rios 2006). Since 2002, southern California has experienced a general reduction in annual rainfall, which has been hypothesized as the sole oak mortality factor for several years (Western Regional Climate Center 2008).

In May and June 2008, we became aware of previously undocumented woodborer damage to the main stem of oaks in San Diego Co. and now consider this insect activity to be the primary or secondary cause of tree mortality. Specifically, buprestid (Coleoptera) larvae were observed and collected in San Diego Co. as the principal group of insects found feeding aggressively in the main stem of *Q. agrifolia* and *Q. kelloggii*. These larvae were identified by the authors to the genus *Agrilus* (Peterson 1951, Stehr 1991). Adults were reared in emergence cages (Browne 1972) from freshly cut logs of *Q. agrifolia*, and pupae were hand collected from the outer bark of infested trees and reared to the adult stage. Adults were also trapped by using three-sided, sticky purple flight-intercept prism traps (30.5 cm × 60 cm) (Synergy Semiochemicals Corp., Burnaby, BC, Canada) hung at 3 m on aluminum conduit poles and baited with a high release ethanol attractant (load 139.3 g, release rate 200–300 mg/day, >98% chemical purity, product #IP036-100, Synergy Semiochemicals). Adults were tentatively identified as *Agrilus coxalis* Waterhouse, 1889 by the authors by using species descriptions (Fisher 1928, Hespenheide 1979), distributional records (Westcott 2005), and through consultation with R.L. Westcott (Oregon Department of Agriculture). The identification was verified by C.L. Bellamy (Plant Pest Diagnostic Laboratory, California Department of Food and Agriculture) and H.A. Hespenheide (University of California, Los Angeles). Voucher specimens of the adult were placed at the California Academy of Sciences, San Francisco, California, and the common name of goldspotted oak borer, reflecting the diagnostic six golden yellow pubescent spots on the elytral surface, has been formally proposed to the Entomological Society of America's Committee on the Common Names of Insects.

Record- CA: San Diego Co., Pine Valley, near Cleveland National Forest, Noble Canyon Trailhead, 32.84889°N, 116.52235°W, VI-27-2008, coll. T.W. Coleman, *ex*: purple flight intercept traps (stickem coated) placed near California coast live oak trees, *Quercus agrifolia*.

Literature Review

To our knowledge, this is the first record of *A. coxalis* (or any buprestid in the genus) attacking the main stem of *Quercus* in California or nearby Mexico (Furniss and Carolin 1977, Cibrian et al. 1995, Solomon 1995, Swiecki and Bernhardt 2006). These observations and collections also confirm larval habits and the host of development for *A. coxalis*, which were unknown. *Agrilus coxalis* was first collected in California in 2004 in Cuyamaca Rancho State Park (San Diego Co.) in flight traps as part of an exotic woodboring beetle survey by the California Department of Food and Agriculture (Westcott 2005). Aerial survey data suggests this insect may have arrived prior to 2002, because of the slowly expanding pattern of *Quercus* mortality in this area. The presence of *A. coxalis* in southern California represents either an introduction or range expansion on new hosts and establishes this species in a winter rainfall regime, as opposed to the monsoon-dominated regions where it has been known to occur (Westcott 2005).

Figure 1. Known distribution of the goldspotted oak borer, *Agrilus coxalis*, and associated oaks, *Quercus* sp., in North and Central America. Previous collection sites are noted in yellow; the lectotype and paralectotypes are designated in red and green, respectively. Locality data were derived from the literature (see text) and from surveys of the following insect collections (AMNH, BMNH, CAS, CIDA, CLBC, CMNC, CNCI, CSCA, EMEC, FSCA, LACM, MCZ, RHTC, RLWE, SBNM, SDMC, TAMU, UAIC, UCDC, UCR, and USNM). Collection codes follow the list "Insect and Spider Collections of the World" maintained by the Bishop Museum (www.bishopmuseum.org/bishop/ento/codens-r-us.html) and underlined codes indicate collections with specimens of *A. coxalis.* Personal correspondence with H.A. Hespenheide and R.L. Westcott facilitated our knowledge of museum holdings outside of California. Specimens at the CAS (AZ: Chiricahua Mts., VIII-10-1908, Van Dyke Collection); UAIC (AZ: Santa Catalina Mts., VII-24-1965); and USNM (Mexico: Tamaulipas, 10 m E Tula, 1189 m elev., V-10-1994) had not been recorded before in the literature or by the specialists.

Previous collections of *A. coxalis* outside of California ranged from southeastern Arizona to Guatemala (Fig. 1), including Arizona: Chiricahua, Huachuca, Santa Catalina, and Santa Rita Mountains (Schaeffer 1905, Fisher 1928, H.A. Hespenheide personal communication in litt., CAS, and UAIC (see Fig. 1 Legend)); Mexico: La Laguna, Sa. Victoria, Sierra de La Laguna (Baja California Sur) (Westcott 2005), Juquila (Oaxaca) (Hespenheide 1979), Tula (Tamaulipas) (see Fig. 1 Legend), Mitla (Oaxaca) (R.L. Westcott personal communication in litt.), Comitán, Lagos de Montebello National Park, Ocosingo, San Cristóbal de las Casas, Teopisca (all Chiapas), and Cordova and Jalapa (Veracruz) (Waterhouse 1889, H.A. Hespenheide personal communication in litt.); and Guatemala: Capetillo (Sacatepéquez), Chilasco, and San Jerónimo (both Verapaz) (Waterhouse 1889, Hespenheide 1979, H.A. Hespenheide personal communication in litt.). The collection in 1977 from Baja California Sur (collected by beating branches of *Quercus* spp.) is considered a range expansion (Westcott 2005).

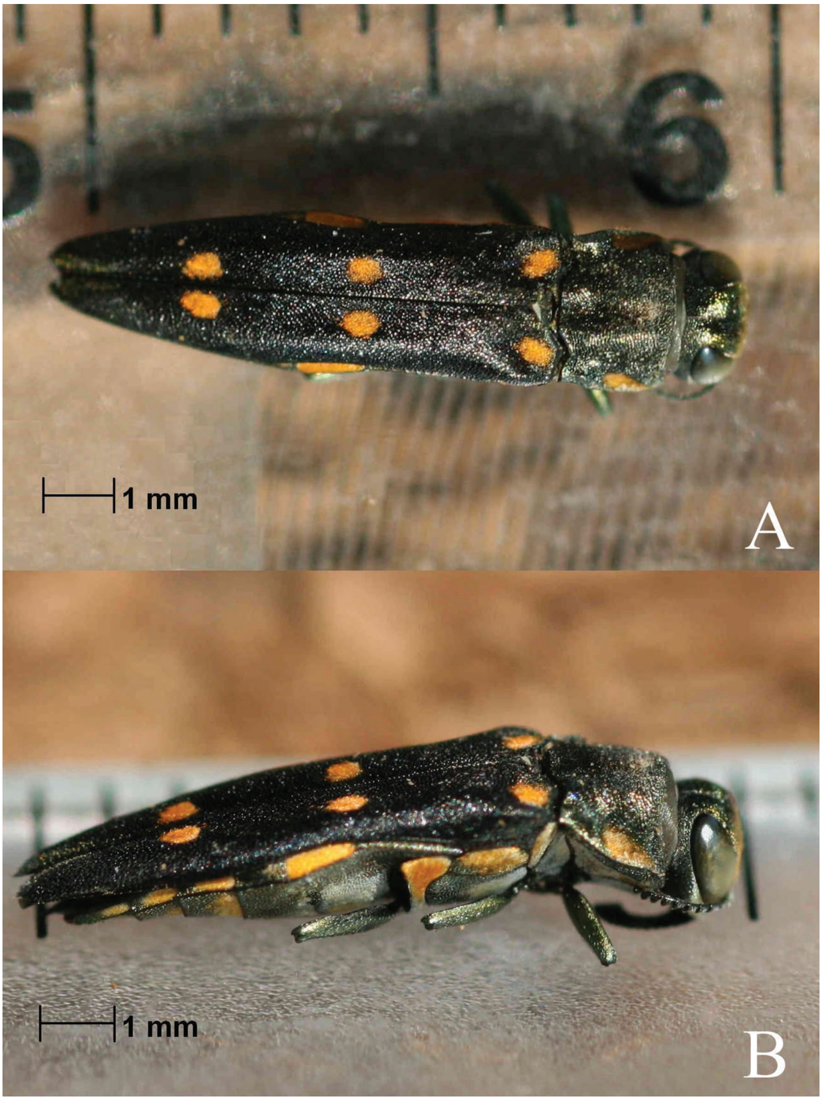

Figure 2. Dorsal (A) and lateral (B) views of the adult of the goldspotted oak borer, *Agrilus coxalis*, found attacking coast live oak, *Quercus agrifolia*, canyon live oak, *Q. chrysolepis*, and California black oak, *Q. kelloggii*, in San Diego Co., California.

Agrilus coxalis has two synonyms: *A. auroguttatus* Schaeffer, 1905 and *A. socus* Obenberger, 1935 (Hespenheide 1979), and the etymology of the proposed common name (goldspotted) is reflected in the Latin translation of the species name of the former synonym. Palmerlee, Huachuca Mountains, Arizona is the type locality of *A. auroguttatus* (Fisher 1928); a female specimen from Juquila, Mexico was designated as the lectotype of *A. coxalis*, whereas another specimen from Juquila, one from Cordova, one from Capetillo (Guatemala), and one from San Jerónimo (Guatemala) were designated paralectotypes (Hespenheide 1979). All of the latter specimens are in the British Museum. The U.S. form and the southern Mexican and Guatemalan form differ in the pubescence (larger and more golden-colored elytral spots in the U.S. specimens) and the shape of the prehumeral carina (Hespenheide 1979), suggesting the potential for subspecific distinction (H.A. Hespenheide personal communication in litt.), which is reinforced by the apparent widely disjunct nature of the currently recorded distribution (Fig. 1).

Host information from the collection history is sparse, but specimens have been associated with silverleaf oak, *Quercus hypoleucoides* A. Camus, *Quercus* spp., and 'black oak,' possibly *Q. devia* Goldman. Adults have been collected on several occasions from oak foliage (Westcott 2005; R.L. Westcott personal communication in litt.). Netleaf oak, *Quercus rugosa* Née, is a common species found at collection sites in southeastern Arizona, southern Baja California, and northern and southern parts of Mexico; we hypothesize that it may be another developmental host of *A. coxalis*. Previous adult *A. coxalis* collections throughout its range have occurred from May 11–September 28, but primarily from May through July (Fisher 1928, Westcott 2005: H.A. Hespenheide personal communication in litt.).

OBSERVATIONS ON THE LIFE HISTORY AND COMMUNITY ECOLOGY OF *A. COXALIS* IN CALIFORNIA

Agrilus coxalis adults are a dull metallic green with six spots of prominent golden yellow pubescence on the elytra (Fig. 2). Mean length and width ($N = 53$) of the adults were 9.4 ± 0.1 mm and 2.1 ± 0.1 mm (both mean $\pm$ s.e), respectively. Adults were trapped on eight purple-colored sticky traps at two sites on the CNF (Barrett Lake and Descanso, see below) (4 traps/site). Peak trap catch (24.8 ± 8.0 beetles/trap/day, mean $\pm$ s.e) occurred during the first week that the traps were installed (June 20 to 27, 2008) (Fig. 3), suggesting that flight begins earlier in the season. Approximately 80% of the total trap catch of 473 beetles was recorded between June 20 and July 17 across both sites. Flight activity declined following July 17, but adults were still caught between October 28 and November 5. In agreement with this long flight period, adults emerged between June and October from *Q. agrifolia* logs in a laboratory rearing cage.

Larvae of *A. coxalis* (Fig. 4) feed primarily on the surface of the sapwood where their galleries are extensive. Mature larval galleries are 4 mm in width, black in color, and tightly packed with frass (Fig. 5). Galleries also extend into the inner and outer bark but at lower densities. Larval galleries etched on the sapwood surface have a meandering appearance with a general vertical orientation (Fig. 6), and are vaguely similar to those of the twolined chestnut borer, *Agrilus bilineatus* Weber, 1801 (Solomon 1995). The galleries of *A. coxalis* were present at the base of trees and extended upward to approximately 9 m along the main stem and larger branches. Mature larvae were observed beneath the bark beginning in May and as late as October. Full season observations will no doubt reveal the presence of young larvae prior to May. Larvae were collected from the outer bark in a hairpin configuration, most likely preparing to pupate. Pupae were collected only from the outer bark, and were observed in mid- to late June and in early October. This suggests that although most of the population likely completes one generation in a year, some fraction of the population may require more than one year to develop. Eggs of *A. coxalis* were not observed.

Once tree mortality has occurred, evidence of ambrosia beetles, *Monarthrum* sp., bark beetles, *Pseudopityophthorus* sp. (both Scolytidae *sensu* Wood 2007); lead cable borer, *Scobicia declivis* LeConte, 1857 (Bostrichidae); oak cordwood borer,

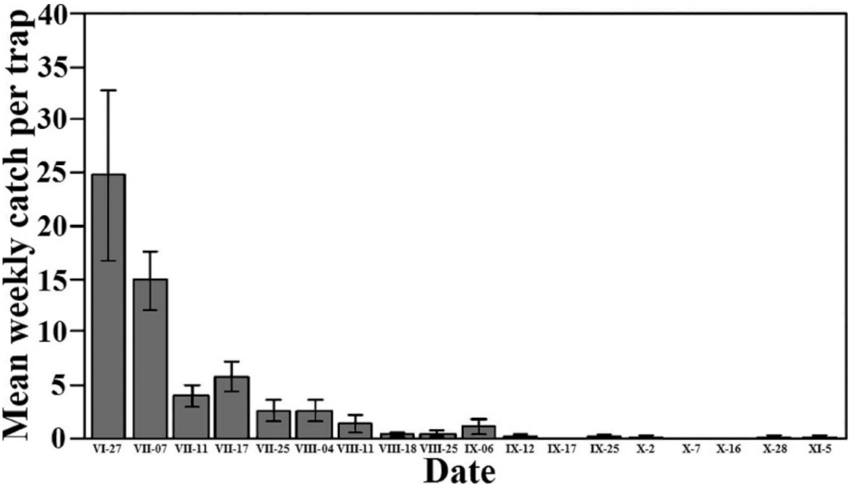

Figure 3. Weekly catch per trap (mean ± s.e., $N = 8$, total trap catch = 473) of the goldspotted oak borer, *Agrilus coxalis*, on purple prism flight-intercept traps in San Diego Co., California during 2008.

Xylotrechus nauticus Mannerheim, 1843; and *Phymatodes* sp., probably *lecontei* Linsley, 1938 (both Cerambycidae) was observed. Larvae of other flatheaded borers were absent from these trees (Swiecki and Berhardt 2006). Ichneumonid (Hymenoptera) parasitoids were also found searching and ovipositing on one *Q. agrifolia* with brown foliage.

Figure 4. Larvae of the goldspotted oak borer, *Agrilus coxalis*, collected from the outer bark of coast live oak, *Quercus agrifolia*, during June 2008 in San Diego Co., California.

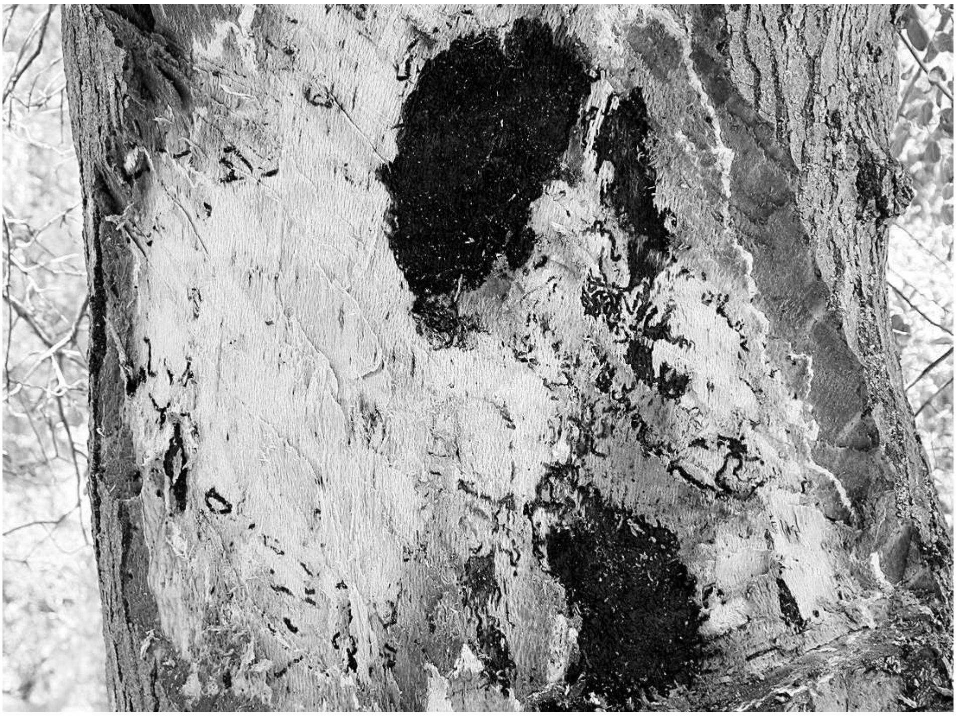

Figure 5. Removal of the bark of coast live oak, *Quercus agrifolia*, reveals extensive black larval galleries of the goldspotted oak borer, *Agrilus coxalis*. High density larval feeding activity on the phloem and sapwood surface results in patch- or strip-killed areas of the cambium; these areas of tissue often exude sap when the bark is removed.

DAMAGE SURVEY, FOREST STAND CONDITIONS, AND TREE SYMPTOMS

Oak mortality was assessed in the Descanso Ranger District during June and July 2008. Surveys were conducted in the localities of Barrett Lake (32.83235°N, 116.51995°W; 1130 m), Descanso (32.85136°N, 116.52222°W; 1097 m), and Mount Laguna (32.85755°N, 116.46422°W; 1666 m), San Diego Co., California. *Quercus agrifolia* is the dominant tree species at Barrett Lake and Descanso, whereas *Q. kelloggii* is abundant on Mount Laguna. The forest canopies are principally single-story with an understory composed largely of shrubs and herbaceous species. Very little natural regeneration of *Quercus* spp. is found at all three sites. Forest canopies are open with little canopy closure at Barrett Lake and Descanso. Forests on Mount Laguna are primarily closed canopy. Site visits in August and September 2008 to the north and south of these localities revealed additional very recent mortality of *Q. agrifolia*, *Q. chrysolepis*, and *Q. kelloggii* caused by *A. coxalis*. The extent of the tree mortality associated with *A. coxalis* encompasses an approximate north-south range of 50 km (Fig. 7).

Living and dead oak trees were assessed for causes of decline and mortality. More than 200 oak trees were surveyed across all three localities. Tree crowns and bark exterior on the stem were examined for external evidence of insect herbivory; the bark was removed to the sapwood to assess for internal evidence. Observations of *A.*

Figure 6. Close-up of the larval galleries of the goldspotted oak borer, *Agrilus coxalis*, on the surface of the sapwood of coast live oak, *Quercus agrifolia*, in San Diego Co., California.

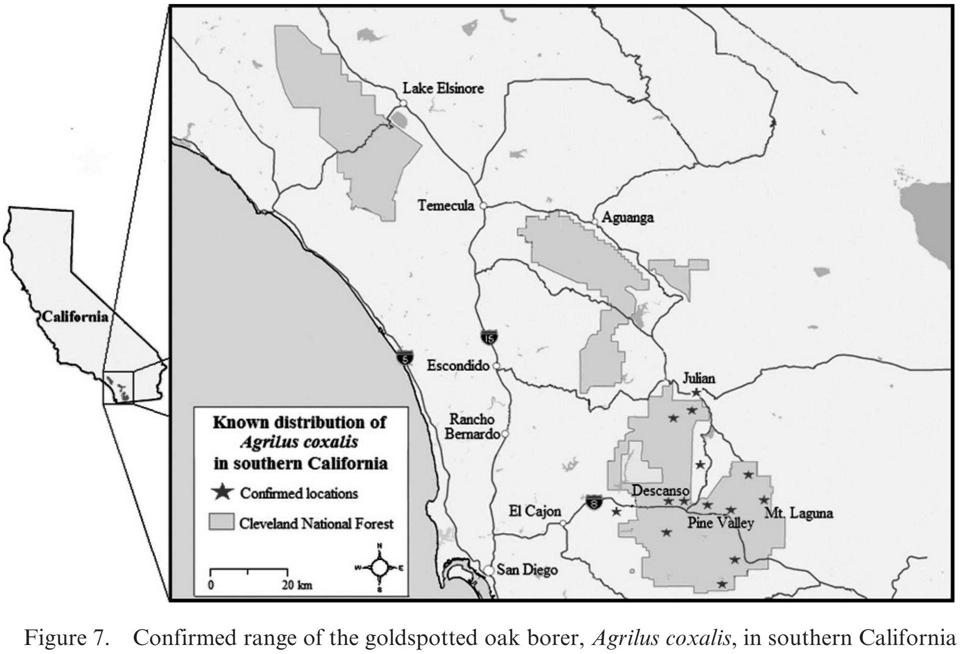

Figure 7. Confirmed range of the goldspotted oak borer, *Agrilus coxalis*, in southern California as of January 2009, based on specimen collection and damage characteristics on oak, *Quercus* spp.

Table 1. Forest stand conditions and prevalence of herbivory from the goldspotted oak borer, *Agrilus coxalis*, at three sites on the Cleveland National Forest June and July 2008.

Forest stand conditions	Site			Mean site conditions[c]
	Barrett Lake[a]	Descanso[a]	Mount Laguna[b]	
Total stand basal area (m^2/ha)	37.9 (9.2)	28.7 (4.3)	41.3 (4.7)	35.1 (4.0)
Quercus spp. basal area (m^2/ha)	24.2 (7.3)	25.3 (3.1)	23.1 (4.6)	24.4 (3.0)
Total stand density (No. trees/ha)	27.2 (5.3)	25.6 (4.7)	30.7 (5.3)	27.4 (2.8)
Quercus spp. density (No. trees/ha)	21.6 (4.7)	23.2 (5.0)	16.0 (8.3)	20.9 (3.0)
Quercus spp. with *A. coxalis* (No. trees/ha)	12.0 (3.6)	16.8 (1.5)	13.3 (5.8)	14.2 (1.9)
A. coxalis-caused mortality (No. trees/ha)	3.2 (1.5)	1.6 (0.9)	4.0 (2.3)	2.8 (0.8)

[a] The table entries in these columns are mean (s.e.), $N = 5$.
[b] The table entries in this column are mean (s.e.), $N = 3$.
[c] The table entries in this column are mean (s.e.), $N = 13$.

coxalis life history, activity of associated insects, *Quercus* decline symptoms, and forest stand conditions were recorded.

Thirteen fixed-radius plots (0.04 ha) were established surrounding oaks to assess forest stand composition, total tree density (ha), and basal area (m^2/ha) across the three sites. Basal area of *Quercus* represented 69% of the total stand basal area (m^2/ha) and 78% of the forest stand density (Table 1). Sixty-seven percent of the oaks were found with external or internal evidence of *A. coxalis* attack (Table 1). Currently, there is an average of three dead oak trees per hectare (13%). Smaller diameter trees (<12.7 cm diameter at breast height) were found with no internal or external evidence of wood-borer herbivory (data not shown).

Quercus agrifolia and *Q. kelloggii* each possess similar external symptoms from *A. coxalis* feeding. However, evidence of insect attack is not as obvious on *Q. kelloggii* compared to *Q. agrifolia*. This is possibly a result of the darker colored and deeper fissured bark of *Q. kelloggii* or differences in host suitability. Woodpecker foraging, which uncovers larval galleries in the outer bark, is very common on the main stem and larger branches of *Q. agrifolia* (Fig. 8). Woodpecker feeding reveals the brick-red outer bark, which is a stark contrast from the gray-colored surface of the bark. Older feeding scars appear darker in color and are less apparent. Woodpecker foraging was infrequently observed on *Q. kelloggii*. Typical of the genus, *A. coxalis* creates D-shaped exit holes (approx. 3 mm in width) when it leaves the main stem, and these holes were numerous on dead and dying trees.

Bark staining was common from the root collar to larger branches. Staining can appear as black and red stains or oozing sap, which may seep from under the bark or appear as blistering. The bark may crack around stained regions. Areas of staining were found to range in diameter from 2 to 16 cm. When the bark was removed from stained areas, a large volume of sap frequently exuded from the wound. Extensive larval galleries were revealed beneath stained bark; the sapwood was scored by feeding activity and this "patch- or strip-killed" the cambium (Fig. 5). Staining can reach high densities on large diameter trees. Several trees were observed producing callus tissue in an attempt to wall off larval feeding.

Tree crowns appeared to thin and die back progressively as the health of the trees declined. Trees with visible insect damage showed signs of premature leaf drop, twig die back, and branch die off. *Quercus agrifolia* crowns with extensive thinning

Figure 8. Evidence of woodpecker foraging and bark staining are common signs of attack by the goldspotted oak borer, *Agrilus coxalis*, on coast live oak, *Quercus agrifolia*.

appeared gray when compared to the dark green color of healthier crowns. Initial signs of crown thinning begin at twig ends (Fig. 9A) and progress down to larger branches (Fig. 9B). A large amount of foliage is retained on *Q. agrifolia* until tree mortality occurs and foliage turns brown. New foliage was found on trees with *A. coxalis* attacks. *Quercus kelloggii* does not appear to retain foliage for longer durations due to leaf abscission in the fall.

Conclusions and Implications

The biological characteristics and damage reported here for *A. coxalis* suggest that this insect might be ranked in pest status (Coleman and Seybold 2008) amongst the group of other tree-killing buprestids that threaten hardwoods in the Northern

Figure 9. Crown die back from attack by the goldspotted oak borer, *Agrilus coxalis*, progresses from the twig ends (A) and down to larger branches (B) on coast live oak, *Quercus agrifolia*.

Hemisphere, e.g., the bronze birch borer, *A. anxius* Gory (Katovich et al. 2000); the oak buprestid, *A. biguttatus* (F.) (Moraal and Hilszczanski 2000); the twolined chestnut borer, *A. bilineatus* (Weber) (Haack and Acciavatti 1992); and the emerald ash borer, *A. planipennis* Fairmaire (McCullough and Roberts 2002). These insects all have relatively similar life histories, feeding behaviors, and host relationships centered primarily on the stems of stressed or declining standing hardwood trees. Colonization of trees by *A. coxalis* and its association with oak mortality have not previously been documented within its known native distribution, and the insect was only first collected in California in 2004. We hypothesize that *A. coxalis* was either recently introduced into California or has expanded its range.

Oak mortality that we now attribute to *A. coxalis* was mapped initially around the town of Descanso in 2002. Descanso is adjacent to the CNF and Cuyamaca Rancho

State Park, both highly visited recreational areas. Descanso and nearby Pine Valley may be the point of establishment in southern California. Anecdotal reports suggest that oak firewood was frequently brought into the area from Mexico for 20 years, and possibly represents a method of introduction from other parts of the native range (A. Shreve, USDA Forest Service, Descanso Ranger District, CNF, personal communication).

Establishment of *A. coxalis* in southern California appears to represent new host associations regardless of whether the species was introduced or has expanded its range. *Quercus engelmannii* has a very limited native distribution from Pasadena to San Dimas and south to eastern San Diego Co., California. *Quercus kelloggii* is found primarily in California, but also ranges north to Oregon (Fig. 1). *Quercus chrysolepis* has a similar distribution to *Q. kelloggii*, but also has a disjunct distribution throughout Arizona. The distribution of *Q. agrifolia* extends from northern Baja California into California, but is predominantly found along the southern and central coast of California. Thus, *A. coxalis* had no geographic overlap with most of these hosts in its previously reported distribution in Arizona, Guatemala, and Mexico but now has the potential to spread further north in California on *Q. agrifolia*, *Q. chrysolepis*, and *Q. kelloggii* and attack other native *Quercus* spp. in more northern latitudes of California.

Agrilus coxalis is playing a significant role in the current oak mortality, either as a primary or secondary pest. Lack of natural population control and intolerance of California's oaks to herbivory from *A. coxalis* may explain the high levels of tree mortality. On the other hand, evidence that trees are creating callus tissue and walling off the attack zone implies that trees may tolerate low levels of attack when healthy. Stress brought on by drought may be predisposing trees to mortality from *A. coxalis*, as has been reported for *A. anxius* on birch (Katovich et al. 2000) and *A. biguttatus* and *A. bilineatus* on oak (Dunn et al. 1986, Moraal and Hilszczanski 2000). These species of *Agrilus* are considered secondary pests that exploit stressed trees.

Additional surveys are needed to determine the complete distribution of *A. coxalis* in California and Baja California, and further research is needed to determine the developmental and activity periods, level of within-tree host utilization, range of suitable hosts, and suppression options in southern California. Initial work suggests that purple flight intercept prism traps are very effective at collecting adults. Furthermore, southern California is very prone to wildfire activity. Increased levels of oak mortality can significantly alter the structure and composition of fuel loads across the landscape, thus increasing the risk to humans. Forest managers should focus on these potential hazards.

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