Timothy D. Paine · François Lieutier
Editors

Insects and Diseases of Mediterranean Forest Systems

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Editors
Timothy D. Paine
Department of Entomology
University of California
Riverside, CA, USA

François Lieutier
Faculté des Sciences
Université d'Orléans
Orléans Cedex 2, France

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Chapter 22
Goldspotted Oak Borer in California: Invasion History, Biology, Impact, Management, and Implications for Mediterranean Forests Worldwide

Tom W. Coleman and Steven J. Seybold

Abstract In 2008, the goldspotted oak borer, *Agrilus auroguttatus* Schaeffer (Coleoptera: Buprestidae), was first linked to elevated levels of oak mortality in southern California (CA), but it appears to have impacted oak woodlands and mixed conifer forests across all land ownerships in this region for nearly two decades. This unexpectedly damaging indigenous exotic phloem- and wood-boring pest is hypothesized to have been introduced in the late 1990s to early 2000s *via* infested firewood from southeastern Arizona to San Diego County, CA. The life history and impact of *A. auroguttatus* on oaks were unknown in its native range prior to 2008, and confusion surrounding its taxonomic placement further complicated the status of this emerging pest problem. The primary tree species infested in CA are coast live oak, *Quercus agrifolia* Née, and California black oak, *Quercus kelloggii* Newb. As the invaded range expands, *A. auroguttatus* may interact with the broader community of other exotic and native pests of oaks in CA and continue to cause ecological and economic impacts. Early detection of *A. auroguttatus* is an imperative prerequisite for managing this invasive species and preventative and suppression treatments have been developed to protect high-value oaks. The movement of infested firewood will likely result in additional satellite infestations across the range of susceptible hosts from Baja California Norte, Mexico to southern Oregon. *Agrilus auroguttatus* currently represents the most significant insect threat to oaks in CA, but, if they are introduced, other European and eastern North American *Agrilus* species also threaten these Mediterranean forest ecosystems.

T.W. Coleman (✉)
Forest Health Protection, USDA Forest Service, 602 S. Tippecanoe Ave,
San Bernardino, CA 92408, USA
e-mail: twcoleman@fs.fed.us

S.J. Seybold
Pacific Southwest Research Station, USDA Forest Service, Davis, CA 95616, USA

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22.1 Threats to Oak Woodlands in Mediterranean Ecosystems

Oak savannas and woodlands are ecologically and economically vital components of Mediterranean forest ecosystems in northern Africa, southern Europe, and southwestern North America. Deciduous and evergreen oak species dominate and co-dominate the canopy cover in flood plains, riparian corridors, coastal habitats, semi-arid foothills and mixed-conifer forests in these regions (Brasier and Scott 1994; Pavlik et al. 1996). These savannas and woodlands provide habitat and a food source for wildlife, and they support grazing (Brasier 1996; Pavlik et al. 1996). Wood or oak bark from these Mediterranean forest ecosystems are valued for lumber, fuel, and cork [e.g., cork oak, *Quercus suber* L. (Section *Cerris*)] (Brasier 1996).

Since the end of the nineteenth century, oak declines impacting several species have been reported from Central Europe and the Mediterranean region (Brasier and Scott 1994; Gibbs and Greig 1997; Fuhrer 1998; Thomas et al. 2002; Jurc et al. 2009; Sallé et al. 2014). A complex of abiotic and biotic factors, including air pollution, drought stress, flooding, warming climate, frost damage, defoliation by insects, bark beetles, wood borers, pathogenic fungi, bacterial infection, and anthropogenic disturbances have been suggested as catalysts or contributors in oak declines in Europe (Brasier and Scott 1994; Fuhrer 1998; Moraal and Hilszczański 2000; Thomas et al. 2002; Jurc et al. 2009; Sallé et al. 2014; Brown et al. 2015). In general, exotic insects and pathogens have not been reported as primary aggressors in these European oak declines. However, a range expansion of the oak splendor beetle, *Agrilus biguttatus* (F.) (Coleoptera: Buprestidae), may be a new component of oak decline in Europe (Gibbs and Greig 1997; Moraal and Hilszczański 2000; Jurc et al. 2009), and *Phytophthora cinnamomi* Rands (Pythiales: Pythiaceae), an exotic root pathogen, has been linked to oak decline in the Iberian region (Brasier et al. 1993; Thomas et al. 2002). In the oak woodlands of California (CA), where a Mediterranean climate prevails in North America, oak declines have not been a common occurrence historically. However, over the last several decades widespread oak mortality along the central coast of CA and north to Oregon has been associated with infection of red oaks (*Quercus* section *Lobatae*, Nixon 1993; Manos et al. 1999) by *Phytophthora ramorum* Werres et al., the causal agent of sudden oak death (Rizzo and Garbelotto 2003; Grünwald et al. 2008, 2012). Urbanization, and wildfire are also threatening deciduous and evergreen oak species in CA oak savannas and woodlands.

22.2 Indigenous Exotic Species

The number of non-indigenous (alien, exotic) forest insect species continues to rise in North America commensurate with increasing levels of international trade (Haack 2006; Langor et al. 2009; Klepzig et al. 2010), and phloem- and wood-boring species have increased dramatically within the United States of America (USA) (Aukema et al. 2010). The establishment and impact of non-indigenous species in naïve ecosystems may depend on several factors, including the size of the founding population, absence of co-evolved natural enemies, insufficient plant resistance, and absence of competitors for host resources (Liebhold et al. 1995; Brockerhoff et al. 2006). The spread of non-indigenous insects is dictated by population growth and dispersal, but the ultimate invaded range of a species is also dictated by the available ecological *niche* and accessibility of habitats suitable for existing populations (Liebhold et al. 1995; Venette et al. 2010). Oceans, deserts, and mountain ranges have acted as natural barriers to limit the spread of populations and influence species divergence and speciation (Mayr 1963). The movement of *indigenous* species across these natural barriers into naïve ecosystems *via* range expansion or human-assisted dispersal can also result in urban tree and forest management concerns. The organisms that partake in this phenomenon have been referred to as “indigenous exotic” or “intracontinental invasive” species (Dodds et al. 2010; Coleman and Seybold 2011).

In the USA, examples of indigenous exotic forest insects include the Mexican soapberry borer, *Agrilus prionurus* Chevrolat (Coleoptera: Buprestidae) (Billings and Pase 2008); the bronze birch borer, *Agrilus anxius* Gory (Carlos et al. 2002); two other flatheaded borers, *Chrysobothris costifrons costifrons* Waterhouse, and *C. analis* LeConte (Basham et al. 2015; Westcott et al. 2015); the locust borer, *Megacyllene robiniae* (Forster) (Coleoptera: Cerambycidae) (Galford 1984); the longhorned beetle, *Neospondylis upiformis* (Mannerheim) (Cerambycidae) (Smith and Hurley 2005); the sixspined ips, *Ips calligraphus* (Germar) (Wood and Stark 1968), the Douglas-fir beetle, *Dendroctonus pseudotsugae* Hopkins (Dodds et al. 2010), the walnut twig beetle, *Pityophthorus juglandis* Blackman (Seybold et al. 2013) (all Coleoptera: Scolytidae) (Bright 2014); and the Nantucket pine tip moth, *Rhyacionia frustrana* (Scudder) (Lepdioptera: Tortricidae) (Yates et al. 1981). The fir bark beetle, *Polygraphus proximus* Blandford (Scolytidae) (Baranchikov et al. 2010) and *A. biguttatus* (Pederson and Jørum 2009), are international examples of “indigenous exotics” in western Eurasia and Europe, respectively. The transportation of some of these species has been attributed to discrete pathways of trade within the nursery industry and movement of raw wood materials, whereas others have undergone more continuous range expansions from historical collection records that had been defined by the native distributions of their hosts. Tree injury and mortality associated with these species may be restricted to their native hosts in new ecosystems due to ornamental or off-site plantings. However, some species may colonize and injure novel hosts in the new habitats.

22.3 The Goldspotted Oak Borer, *Agrilus auroguttatus* Schaeffer (Coleoptera: Buprestidae)

In 2004, the goldspotted oak borer, *A. auroguttatus*, was first detected in San Diego Co., CA, approximately 670 km from its native historic range in southeastern Arizona (AZ), USA, representing another example of an indigenous exotic species

(Westcott 2005) (Fig. 22.1). The population has since spread to Riverside, Orange, and Los Angeles Cos., CA (Jones et al. 2013; Coleman et al. 2015). The spread of the established population in CA can likely be attributed to natural dispersal by the beetle and movement of firewood cut from infested trees (Coleman and Seybold 2011).

We hypothesized that infested firewood was also likely the pathway by which *A. auroguttatus* was introduced originally into southern CA (Coleman and Seybold 2008b, 2011). Infested firewood has been associated with the movement of other exotic species in the USA, including the emerald ash borer, *A. planipennis* Fairmaire (Haack et al. 2010). It is less likely that *A. auroguttatus* has expanded its range westward into CA through natural dispersal. *Agrilus auroguttatus* would have had to cross the natural barriers of the Mojave and Sonoran Deserts, which bisect CA and AZ and extend from southern Nevada to Sinaloa, Mexico. Annual plant species and low shrubs dominate these deserts (Shreve and Wiggins 1964), thus isolating the oak hosts of *A. auroguttatus* in each region. Differences between the habitats in CA and AZ are not restricted solely to plant species assemblages, but also extend to other *Agrilus* and the subcortical community of other wood-boring insect species on oaks (Coleman and Seybold 2011). Furthermore, the rainfall regimes are dissimilar between the two regions (Westcott 2005). Arizona is characterized by monsoonal precipitation with rainfall occurring primarily during the summer months, whereas CA is characterized by precipitation that falls primarily during the winter months.

Since 2002, elevated levels of oak mortality occurred continuously in eastern San Diego Co. (USDA FHM 2014). However, *A. auroguttatus* was not linked to tree

Fig. 22.1 Goldspotted oak borer, *Agrilus auroguttatus*, adults feeding on foliage of coast live oak, *Quercus agrifolia*

injury and mortality until 2008 in San Diego Co., CA (Coleman and Seybold 2008a, b). For years oak mortality was thought to be associated with drought, and referred to colloquially as “oak croak,” following several failed investigations to associate the continuing tree mortality with infection by pathogens. Coleman et al. (2011) reported that old growth oaks had the most favorable water status when compared to smaller and mature oaks in the uninfested and infested areas of San Diego Co. Thus, although this largest size class of oaks typically showed the highest probability of infestation by *A. auroguttatus*, these oaks did not appear to be under drought stress. Furthermore, in the same study, early summer plant water status (e.g., branchlet xylem water potential and water use efficiency) was similar for uninfested and newly infested trees, suggesting that *A. auroguttatus* was not pre-selecting drought-stressed trees. It appears that drought stress is not required for *A. auroguttatus* injury and mortality in CA, but drought may increase host susceptibility to this invasive species.

22.4 History of *Agrilus auroguttatus* in Its Native Region and Similar Species

The taxonomic status of *A. auroguttatus* has been in a state of flux for decades. Schaeffer (1905) initially described *A. auroguttatus* from populations in southeastern AZ, but Hespenheide (1979) synonymized *A. auroguttatus* with a similar species, *A. coxalis* Waterhouse, collected only from central and southern Mexico and Guatemala (Fig. 22.2). Following discovery of the invasive population in CA (Westcott 2005; Coleman and Seybold 2008b) and morphological scrutiny of the specimens, Hespenheide and Bellamy (2009) assigned subspecific status to the populations from AZ/CA (*Agrilus coxalis auroguttatus* Schaeffer) and Mexico/Guatemala (*Agrilus coxalis coxalis* Waterhouse). Hespenheide et al. (2011) returned *A. auroguttatus* and *A. coxalis* to species status based on the morphology of the male genitalia. The common name of Mexican goldspotted oak borer has been assigned to *A. coxalis*. Prior to 2008, no life history information was known about either *A. auroguttatus* in AZ or *A. coxalis* in Mexico (Furniss and Carolin 1977; Cibrian et al. 1995; Solomon 1995). Tree mortality was never associated with these two species in their native ranges until the discovery of *A. auroguttatus* in CA.

Molecular analyses of mitochondrial and nuclear ribosomal DNA (mtDNA and rDNA) supported the morphologically-based species status of *A. auroguttatus* and *A. coxalis* (Coleman et al. 2012b). The COI (mtDNA) gene sequences of *A. coxalis* from southern Mexico differed by 11 % from the homologous sequences from *A. auroguttatus* from AZ and CA (Coleman et al. 2012b). Additional analyses revealed that the invasive CA population of *A. auroguttatus* was similar to AZ populations, sharing two mtDNA haplotypes (Lopez et al. 2014c). In addition, examination of the D2 domain of 28S rDNA sequences revealed that the AZ and CA populations were identical, whereas sequences from the Mexican *A. coxalis* population differed from sequences from the AZ–CA populations by 8 base pairs (Coleman et al.

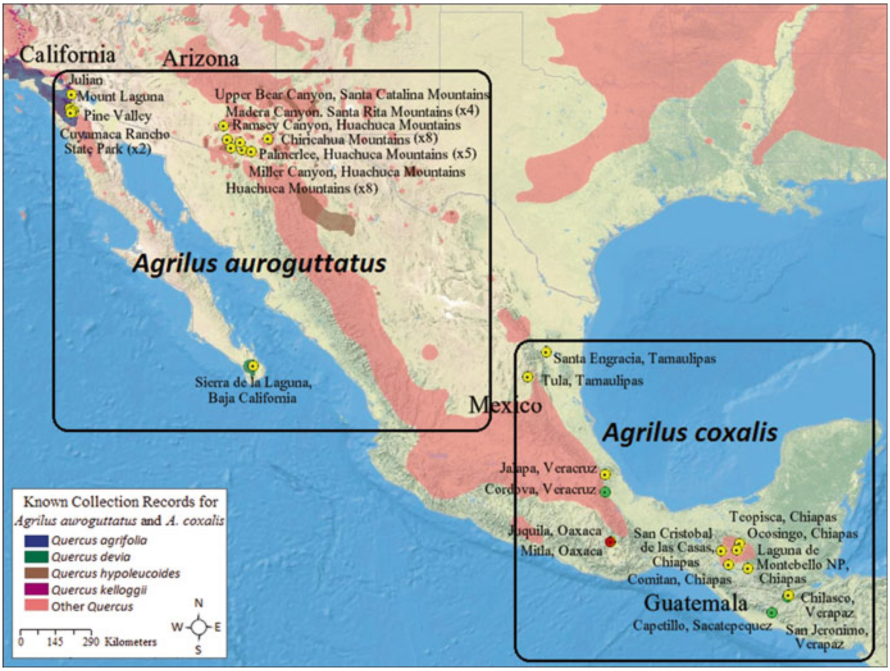

Fig. 22.2 Recorded distributions of the goldspotted oak borer, *Agrilus auroguttatus*, the Mexican goldspotted oak borer, *A. coxalis*, and associated oaks, *Quercus* sp., in North and Central America (Coleman and Seybold 2011). Previous collection sites are noted in *yellow*; the lectotype and paralectotypes for *A. coxalis* are designated in *red* and *green*, respectively. Locality data were derived from the literature and from a survey of museum specimens (Modified from Coleman and Seybold 2008b). Extreme southern collection localities for *A. coxalis* (San Lorenzo, Zacapa, San Lorenzo, San Marcos, Guatemala; and Montaña del Malacate, Olancho, Honduras) are not depicted

2012b). Additional surveys and collections of *A. auroguttatus* across the mountain ranges of the Coronado National Forest in southeastern AZ further confirmed that all of the populations were *A. auroguttatus* and that populations from the Dragoon Mountains in AZ may be the source of the populations in southern CA (Lopez et al. 2014c) (Fig. 22.3).

22.5 *Agrilus auroguttatus* Life History and Biology

Agrilus auroguttatus adults are a dull metallic green with golden-colored pubescent spots on the surface of the thorax and abdomen (Fig. 22.1). Adults are 9.4 (±0.1) mm long and 2.1 (±0.1) mm wide (both mean ± s.e.) (Coleman and Seybold 2008b). Adult males can be distinguished from females by the presence of a median ventral groove on the first abdominal segment, and females are generally larger than males (Coleman and Seybold 2010). Adults feed minimally along the margins of oak

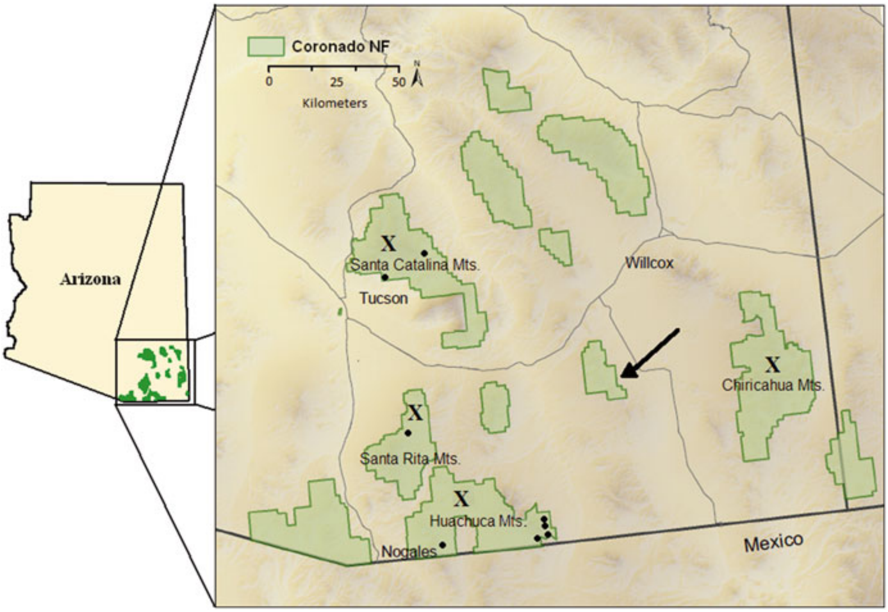

Fig. 22.3 Historical collection records of the goldspotted oak borer, *Agrilus auroguttatus*, from four mountain ranges (Santa Catalina, Santa Rita, Huachuca, and Chiricahua) in the Coronado National Forest in southeastern Arizona (Modified from Coleman and Seybold 2011). General collection localities are denoted by an X, whereas specific locations from collection labels are indicated by *black dots* (•). *Arrow*: Dragoon Mountains-the putative origin of the population of *A. auroguttatus* that has been introduced into California (Lopez et al. 2014c)

leaves, and females must feed to become sexually mature. Females, when paired with a single male, become sexually mature after 8 days with a food source of water and leaves; can have an ovipositional period of 43.6 (±7.4) days; survive for 72.1 (±6.3) days in a laboratory setting; and lay approximately 200 eggs (Lopez and Hoddle 2014). Adult males can survive for 37.1 (±6.0) days under the same conditions. As is the case with other species of *Agrilus*, adult *A. auroguttatus* likely mate in the canopy of host trees or along the main stem (Carlson and Knight 1969; Haack and Acciavatti 1992; Lelito et al. 2007; Rodriguez-Saona et al. 2007). Females of *A. auroguttatus* lay eggs from June to September singly or in clusters on the bark surface or in bark cracks along the main stem and larger branches of oak trees (Flint et al. 2013). Adults begin to emerge in late May and the main flight period extends to September (Coleman et al. 2014a). Peak flight occurs from late June to early July in southern CA. This period of adult activity has been supported by collection dates on numerous specimen records (Coleman and Seybold 2011) and seasonal emergence from infested wood (Jones et al. 2013 and see Management-monitoring techniques below). *Agrilus auroguttatus* is believed to be univoltine, but the life cycle may take 2 years in healthier host trees (Flint et al. 2013; Haavik et al. 2013). In flight mill studies, adults flew a mean distance of 790 m in 24 h (Lopez et al. 2014b).

Eggs of *A. auroguttatus* are tan in color, oval, and less than 0.25 mm in diameter (Flint et al. 2013). Eggs have rarely been observed in the field due to their small size and the inconspicuous oviposition sites. Larvae hatch from eggs approximately 10–15 days after oviposition (Lopez and Hoddle 2013) and likely complete four larval instars (Haavik et al. 2013). Larvae are white in color and legless; they possess C-shaped spiracles along the lateral sides of the abdomen, and two urogomphi at the tip of the abdomen (Fig. 22.4). First instar larvae are about 2 mm long, whereas fourth instar larvae are 20 mm long and 4 mm wide (Flint et al. 2013). After hatching, larvae tunnel through the bark and phloem to the interface of the phloem and xylem. Feeding occurs primarily in this cambial region, and the larvae injure the cambium and phloem

Fig. 22.4 Larva of goldspotted oak borer, *Agrilus auroguttatus*, feeding at the phloem/xylem interface of California black oak, *Quercus kelloggii*, in southern California. This feeding destroys the meristematic cambium and causes necrosis of the phloem (*black stained areas*)

and score the outer xylem (Fig. 22.4). Immature larvae are found primarily from late summer to early fall feeding on the xylem surface in CA (Haavik et al. 2013). Larvae rarely feed in the xylem. Mature larvae return to the outer phloem where they construct a pupal cell just under the outer bark. Mature larvae, or prepupae, constrict into a hairpin configuration in the pupal cell where they remain until the following spring. Found throughout most of the year (mid-October to mid-June) when compared to the other life stages mature larvae/prepupae can be sampled easily from trees to verify infestation or to obtain live material for laboratory studies. Pupation begins to occur during the spring to early summer in southern CA. Pupae are similar in size to adults and white in color until the cuticle begins to melanize and sclerotize.

22.6 Host Range of *Agrilus auroguttatus*

Field observations in CA have recorded that *A. auroguttatus* can attack and reproduce in coast live oak, *Q. agrifolia* Née, California black oak, *Q. kelloggii* Newb., canyon live oak, *Q. chrysolepis* Liebm, and Engelmann oak, *Q. engelmannii* Greene. Red oaks (section *Lobatae*) were killed more frequently by *A. auroguttatus* (*Q. agrifolia*: 91 % and *Q. kelloggii*: 88 %) than white oaks (*Q. engelmannii*: 0 %) in CA (Coleman et al. 2012a). *Quercus chrysolepis*, a goldencup oak, which is a taxonomically intermediate oak species (subgenus *Quercus*, section *Protobalanus*), has been injured and killed by *A. auroguttatus*, but mortality was associated less frequently with this species (60 %) than with the red oaks. We have hypothesized that red oaks are much more susceptible to injury by *A. auroguttatus* with phloem thickness, bark structure, and/or host chemistry as factors that contribute to this susceptibility (Coleman and Seybold 2011). Interior live oak, *Q. wislizenii* A.DC., and Shreve oak, *Quercus parvula* Greene var. *shrevei* (C.H. Mull.) Nixon, two red oak species that are present farther north in CA, are likely to be susceptible to *A. auroguttatus* and may experience elevated levels of tree mortality as the invaded range of *A. auroguttatus* expands. Numerous red and white scrub oak (shrub-like) species occur in the infested area of San Diego Co. and throughout CA, but injury from *A. auroguttatus* has never been recorded on these species. These scrub oak species rarely exceed 12.5 cm diameter at breast height (dbh), which is a key threshold of susceptibility for red oaks to attack by *A. auroguttatus* (see below).

In AZ, the native hosts of *A. auroguttatus* are Emory oak, *Quercus emoryi* Torrey, and silverleaf oak, *Q. hypoleucoides* A. Camus (both section *Lobatae*). The range of these species extends along the southern edge of the Mogollon Rim in central AZ, east into southern New Mexico, and south into Sonora and Chihuahua, Mexico (USDA Forest Service 2009). *Agrilus auroguttatus* prefers to colonize these red oaks more than the white oaks that grow in this region, i.e., AZ white oak, *Q. arizonica* L., and gray oak, *Q. grisea* Liebm. (subgenus *Quercus*, section *Quercus*) (Coleman and Seybold 2011; Haavik et al. 2014a). In southern Mexico, *A. coxalis* was found killing *Q. peduncularis* Née, a white oak. Only low levels of tree mortality have been associated with these sibling species of *Agrilus* in their respective native regions (Coleman et al. 2012a; 2015).

In laboratory host range tests, *A. auroguttatus* was capable of completing larval development in cut logs of *Q. agrifolia*, *Q. kelloggii*, *Q. wislizenii*, *Q. chrysolepis*, *Q. suber*, valley oak, *Q. lobata* Née, and blue oak, *Q. douglasii* Hook. & Arn. (Haavik et al. 2014b) (Fig. 22.5). Gallery construction by *A. auroguttatus* larvae was significantly greater on red oaks when compared to white oaks, to *Cerris* species (*Q. suber* only), and to goldencup species. This supports the hypothesis of greater risk for red oak species than white oak species, goldencup species, and ornamental species in the section *Cerris*. Adult no-choice feeding bioassays on foliage resulted in no statistically significant differences for female longevity, days until fecund, total fecundity, daily oviposition, proportion of eggs melanized, and proportion of eggs hatched across red, white, goldencup, and *Cerris* oak species and a non-host species, white alder, *Alnus rhombifolia* Nutt. (Haavik et al. 2014b). Chen et al. (2013) showed that adult *A.*

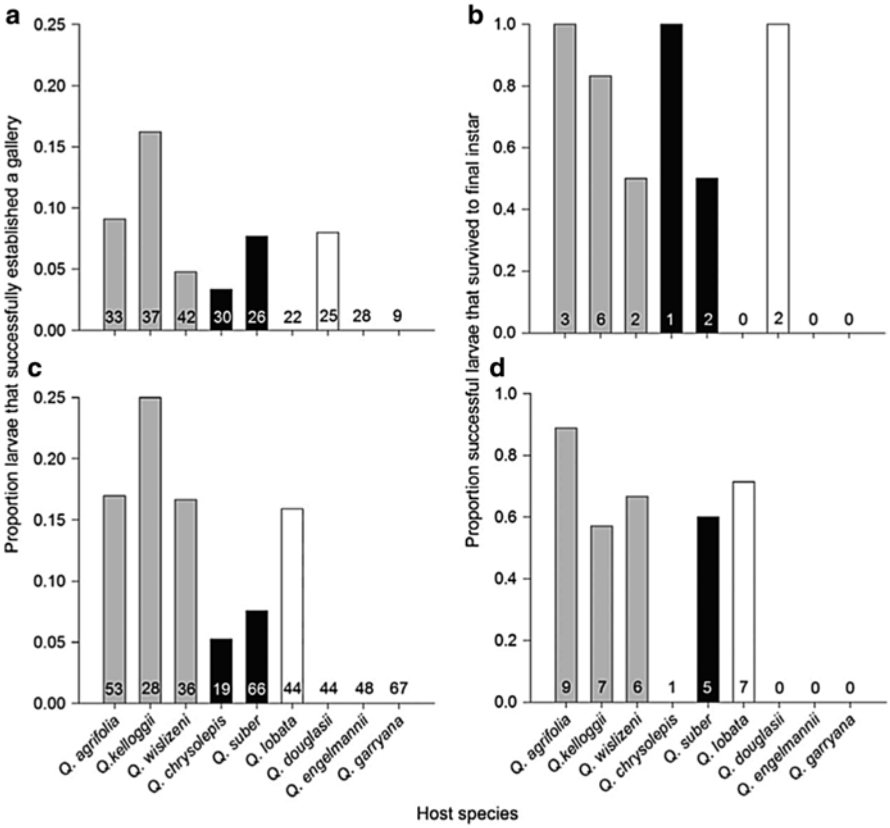

Fig. 22.5 Measurements of host suitability for *Agrilus auroguttatus* grouped by oak species from laboratory tests conducted in 2010 (**a** and **b**) and 2011 (**c** and **d**) (Reproduced from Haavik et al. 2014b). *Gray bars* represent oaks in Section *Lobatae*; *black bars* represent oaks in other sections (*Quercus chrysolepis* Section *Protobalanus*, *Q. suber* Section *Cerris*); and *white bars* represent oaks in Section *Quercus*. A–D were analyzed separately; no difference was significant. Sample sizes are indicated at the base of the bars

auroguttatus consumed more foliar weight and foliar area of *Q. kelloggii* than *Q. agrifolia*, *Q. chrysolepis*, and *Q. engelmannii* in no-choice and dual choice tests, suggesting that *A. auroguttatus* prefers foliage from this red oak species over the other three oak species. Analysis of four macronutrients (nitrogen, sulfur, phosphorus, and potassium) and two micronutrients (zinc and copper) suggests that these nutrients might be directing preferential feeding of *A. auroguttatus* (Chen et al. 2013). *Quercus suber*, holm oak, *Q. ilex* L., and southern live oak, *Q. virginiana* Mill., are frequently planted as ornamental trees in CA; however, we hypothesize these species will be at low risk to *A. auroguttatus* injury and mortality since they are not in the red oak section.

22.7 Injury Symptoms Associated with *Agrilus auroguttatus*

External symptoms of tree injury associated with *A. auroguttatus* can include premature twig dieback and thinning in the crown; D-shaped emergence holes through the bark surface of the stem and larger branches; woodpecker foraging damage to the bark surface; and bark staining or weeping and cracking (Coleman et al. 2011; Hishinuma et al. 2011). As tree injury from *A. auroguttatus* becomes more extensive, crown thinning and dieback worsen progressively, generally from the upper branches to the lower branches in the crown. In the infested areas of CA, severe crown thinning on host oak species has been associated frequently with extensive injury from *A. auroguttatus* larvae and imminent tree mortality. Adult feeding does not likely contribute to crown thinning and is rarely detectable in the field. Distinct twig and branch mortality (i.e., flagging) is not a common injury symptom of *A. auroguttatus* and is frequently associated with injury by other insects (Flint et al. 2013).

Adult emergence of *Agrilus* species leaves a characteristic D-shaped hole (4 mm wide for *A. auroguttatus*) in the outer bark. Emergence holes can be found from the root collar to the larger branches (>20.3 cm in diameter) on host oaks, but the majority of holes are found primarily along the lower main stem (Haavik et al. 2012b). *Agrilus auroguttatus* is the only *Agrilus* species that infests the main stem and larger branches of oaks in CA, making this injury symptom diagnostic for this species in CA (Coleman et al. 2011). Furthermore, no other *Agrilus* species have been reared from *A. auroguttatus*-infested host material in AZ and CA (Coleman and Seybold 2011; Coleman et al. 2012b; Jones et al. 2013). Emergence holes from *A. auroguttatus* occur randomly on the lower bole (<1.52 m) and three random samples collected in 0.09 m^2 quadrats can provide a reliable estimate of injury from this species (Haavik et al. 2012b). The density of *A. auroguttatus* emergence holes in declining oaks was significantly greater than the density of these holes from other wood borers in CA, but this was not the case in its native region of AZ (Haavik et al. 2014a). Secondary wood borers and bark beetles are frequently encountered on *A. auroguttatus*-infested trees once severe tree injury or areas of the phloem and cambium have been patch-killed. Attack from these secondary insects can be distinguished from *A. auroguttatus* by the size and shape of the entrance and emergence holes, the location of injury on the tree, and the density of attacks (Flint et al. 2013).

Bark removed by acorn woodpeckers, *Melanerpes formicivorus* (Swainson), and Nuttall's woodpeckers, *Picoides nuttallii* (Gambel) (both Piciformes: Picidae) as they forage for prepupae in the outer phloem is a frequent sign of infestation in CA (Coleman et al. 2011). Bark removal by woodpeckers foraging in search of *A. auroguttatus* larvae is shallow and penetrates only to the outer phloem. Foraging by other woodpecker species penetrates more deeply to the xylem surface where other wood-boring insect species occur. Woodpecker foraging for *A. auroguttatus* follows the larval gallery in the outer phloem to the pupal cell where the predation occurs. Exposed brick-red phloem of coast live oaks contrasts with the grey outer bark, making this injury symptom very visible at first. The red coloration of the phloem fades to a black color as time passes. The impact of predation from woodpeckers is unknown in CA, but may contribute significantly to reducing population densities of *A. auroguttatus* in nesting areas.

Bark staining or weeping can appear as black patches, wet staining, or red oozing sap on the bark exterior (Hishinuma et al. 2011; Flint et al. 2013). The size of stained bark sections can vary greatly on the bark exterior from <2.4 to 15.2 cm^2 patches. Pockets of sap may accumulate under the bark where the phloem and cambium have been killed by extensive larval feeding. Bark staining is not always present on *A. auroguttatus*-infested trees, but is observed more frequently after severe injury from the beetle has occurred. An ensemble of secondary fungi has been associated with these stained areas in and out of the *A. auroguttatus* infested area in CA (Lynch et al. 2014). The bark often cracks after extensive larval feeding has killed the phloem and cambium and the tissue desiccates under the bark. Crown thinning and bark staining are a general response to declining tree health and do not necessarily signify *A. auroguttatus* infestation in the native and introduced regions. Additional evidence of *A. auroguttatus* infestation must be found to verify injury from this phloem-boring species.

A health rating system was developed based on the external injury symptoms of *A. auroguttatus*, and was disseminated to land managers, pest specialists, and private homeowners to assist with management decisions and to quantify tree injury (Hishinuma et al. 2011) (Fig. 22.6). Crown thinning is ranked on a scale of 1–5 (1: full, healthy crown [0 % leaf loss]; 2: minor twig dieback and/or light thinning [10–25 % leaf loss]; 3: moderate thinning and twig dieback [25–50 % leaf loss]; 4: severe dieback to larger branches [>50 % leaf loss]; and 5: tree is dead); D-shaped emergence hole density is ranked on a scale of 1–3 (1: <10 emergence holes; 2: 10–25 emergence holes, 3: >25 emergence holes on the lower 2 m of the main stem); bark staining is ranked on a scale of 1–4 (1: 1–5 stained areas, 2: 6–10 stained areas, 3: >10 stained areas, and 4: bark cracking is evident on the lower 2 m of the main stem); and the presence or absence of woodpecker foraging damage is also noted. Increases in emergence hole densities were correlated with crown thinning and dieback and the change in density of emergence holes was significantly greater on trees with severe crown thinning (rating of "4," Hishinuma et al. 2011) and recently killed (<1 year) trees (Coleman et al. 2011, See Figure 5.B in Coleman et al. 2014a). Total count of D-shaped emergence holes on the main stem (<2 m) has been the most practical measure of the extent of tree injury from *A. auroguttatus*.

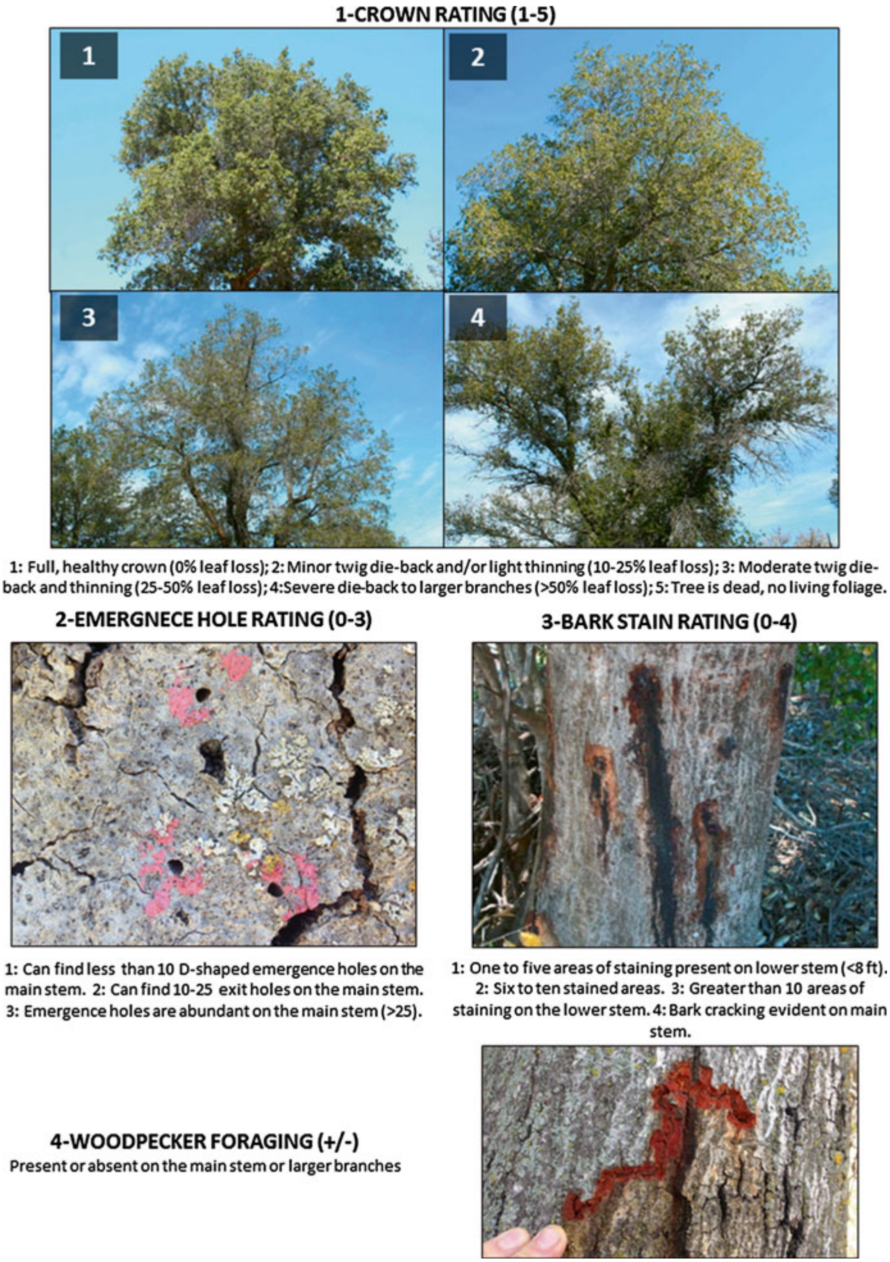

Fig. 22.6 A tree health rating system associated with goldspotted oak borer, *Agrilus auroguttatus*, injury in California. The health rating system incorporates crown thinning/dieback (rank 1–5), adult emergence hole densities (rank 1–3), bark staining/weeping (rank 1–4), and woodpecker foraging (presence/absence) (Modified from Hishinuma et al. 2011; Coleman et al. 2011, 2015)

As the number of emergence holes surpasses 120 on the main stem (<2 m) of *Q. agrifolia*, tree mortality will likely occur in a few years (Fig. 22.7).

Tree injury associated with *A. auroguttatus* is similar to other *Agrilus* species on hardwood trees, including *A. anxius*, twolined chestnut borer, *A. bilineatus* (Weber), and *A. planipennis* (Haack and Acciavatti 1992; Katovich et al. 2000; McCullough and Roberts 2002). However, injury *A. auroguttatus* the larvae does not occur in the branches of the upper crown of a tree. In contrast, larval injury from *A. auroguttatus* is concentrated on the lower bole and larger branches during all stages of infestation, allowing ground surveys to be an effective tool for monitoring these populations and for use in management decisions.

The primary internal injury symptom of *A. auroguttatus* is the dark, meandering larval galleries on the xylem surface (Fig. 22.8). The dark coloration of the galleries is believed to result from the oxidation of injured tree tissue (Coleman et al. 2011). The larval galleries are tightly packed with frass, characteristic of most Buprestidae. Galleries are approximately 4 mm wide when the larvae are mature and lightly score the outer xylem. When larval feeding is concentrated in an area, or feeding becomes very extensive, areas of the phloem and cambium can be strip or patch-killed. Tyloses have been observed in the xylem on trees injured by *A. auroguttatus* and late summer measurements of leaf water potential and cell turgor potential suggest *A. auroguttatus* infestation increases drought stress in trees (Coleman et al. 2011). Furthermore, infested old growth trees with greater *A. auroguttatus* injury exhibited the greatest decline in water use efficiency over a growing season.

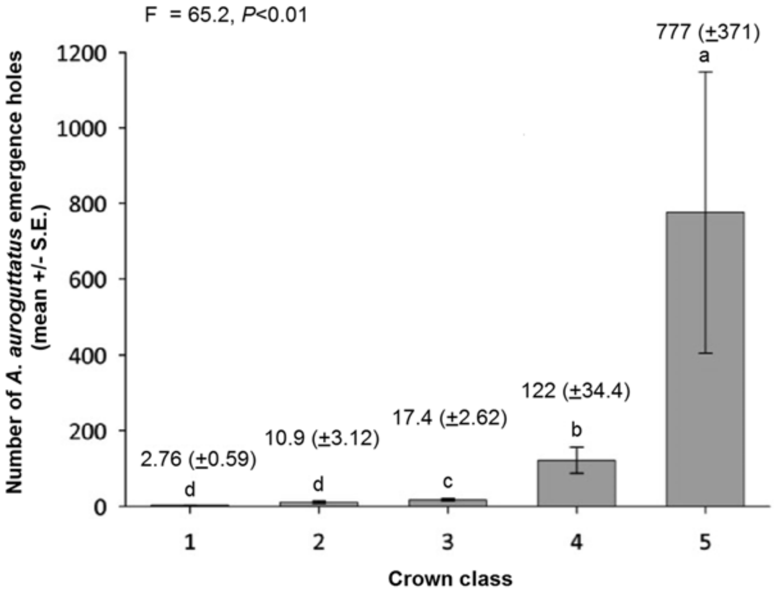

Fig. 22.7 Number of adult goldspotted oak borer, *Agrilus auroguttatus*, emergence holes [mean (± S.E.)] recorded across the five crown health classes of coast live oak, *Quercus agrifolia*, found on the Descanso Ranger District, Cleveland National Forest, San Diego Co. California. Coleman et al. (2014a) presents these data in terms of emergence hole density (See Figure 5.B therein)

Fig. 22.8 Black meandering larval galleries of the goldspotted oak borer, *Agrilus auroguttatus*, on the xylem of California black oak, *Quercus kelloggii*, on the Cleveland National Forest, San Diego County, California

In response to injury from *A. auroguttatus*, wound-induced periderm (i.e., callus) tissue has been observed on the xylem surface in association with larval galleries and in the phloem of host trees (Coleman and Seybold 2008b). Callus tissue formation can be extensive in the phloem, covering large patches of larval feeding. Feeding by *A. auroguttatus* on the callus tissue rarely occurs (Coleman, unpublished data 2013). Callus tissue has been observed on living and dead trees with *A. auroguttatus* injury, suggesting the callus tissue may slow injury by the beetle but does not prevent mortality. A callus response has been observed on *Q. agrifolia* and *Q. kelloggii*, further implying these trees are not under severe stress (Dunn et al. 1990).

22.8 Impact of *Agrilus auroguttatus* with an Emphasis on California

Agrilus auroguttatus prefers to land on, attack, and kill larger diameter oaks in AZ and CA (Coleman et al. 2012a, 2014a; Chen et al. 2015) (Fig. 22.9). In CA, *A. auroguttatus* landing rates were higher on larger (>50.8 cm dbh) than on smaller (25.4–50.8 cm dbh) diameter *Q. agrifolia* and on trees with severe crown thinning (rating of "4," Hishinuma et al. 2011; Coleman et al. 2014a) (Fig. 22.10). Diameters of infested *Q. agrifolia* and *Q. kelloggii* have ranged from 15.8 to 193 cm dbh in CA (Coleman et al. 2012a). Chen et al. (2015) reported that *Q. agrifolia* with diameters between 20 and 41 cm dbh had the greatest cumulative increase in emergence holes over a 2.5-year assessment period. Surveys of oaks killed by *A. auroguttatus* on the Descanso Ranger District of the Cleveland National Forest (San Diego Co.) revealed that 80 % of the dead trees consisted of *Q. agrifolia* that were >43.7 cm dbh and *Q. kelloggii* that were >51.6 cm dbh (Coleman, unpublished data 2013). In AZ, the mean diameters of *Q. emoryi* and *Q. hypoleucoides* infested by *A. auroguttatus* were 43.5 and 29.9 cm dbh, respectively (Coleman et al. 2012a).

The impact of *A. auroguttatus* in CA is characteristic of an invader relative to its impact recorded in AZ and relative to the impact of *A. coxalis* in Mexico (Coleman et al. 2012a). The mean infestation rate for *A. auroguttatus* in San Diego Co. was 61 %, whereas the mean infestation rate in AZ was 4 %, and for *A. coxalis* in Mexico was 3 % (Coleman et al. 2012a). Chen et al. (2015) reported that over a 2.5 year study period at two sites near the core area of the invaded range, the new infestation rates of initially uninfested coast live oaks were 50 % and 32 %. Oak woodlands that have been infested by the exotic beetle for longer than a decade have infestation rates >90 % near the presumed point of introduction of the beetle. High infestations rates were recorded in these areas because, in part, large diameter red oaks dominate the forest cover type (e.g., basal area and tree density per hectare) (Coleman et al. 2012a). The infestation is spreading radially from southeastern San Diego Co., so infestation rates decrease away from the predicted origin of the introduction near Guatay, CA (Coleman et al. 2012a) (Fig. 22.11). However, infestation and mortality levels associated with satellite infestations *via* movement of infested firewood in San Diego Co. may not follow this trend.

Crown injury ratings associated with *A. auroguttatus* and *A. coxalis* were significantly different among the infested areas of AZ, CA, and Mexico and uninfested areas in CA (Coleman et al. 2012a). Healthy crown classes (no crown thinning or dieback, Hishinuma et al. 2011) dominated (>70 %) the sites in AZ, Mexico, and uninfested sites in CA. However, oaks were distributed relatively evenly across the crown rating categories in infested stands in CA, i.e., healthy (28 %), minor thinning (24 %), moderate thinning (20 %), and dead trees (18 %) (Coleman et al. 2012a). Ten percent of the trees were rated with severe crown thinning in the CA infested sites. Newly infested outlier sites in San Diego Co. also had few severely injured trees. These "brood" trees produced 66–93 % of the *A. auroguttatus* population during one year at these newly infested outlier sites (Haavik et al. 2015).

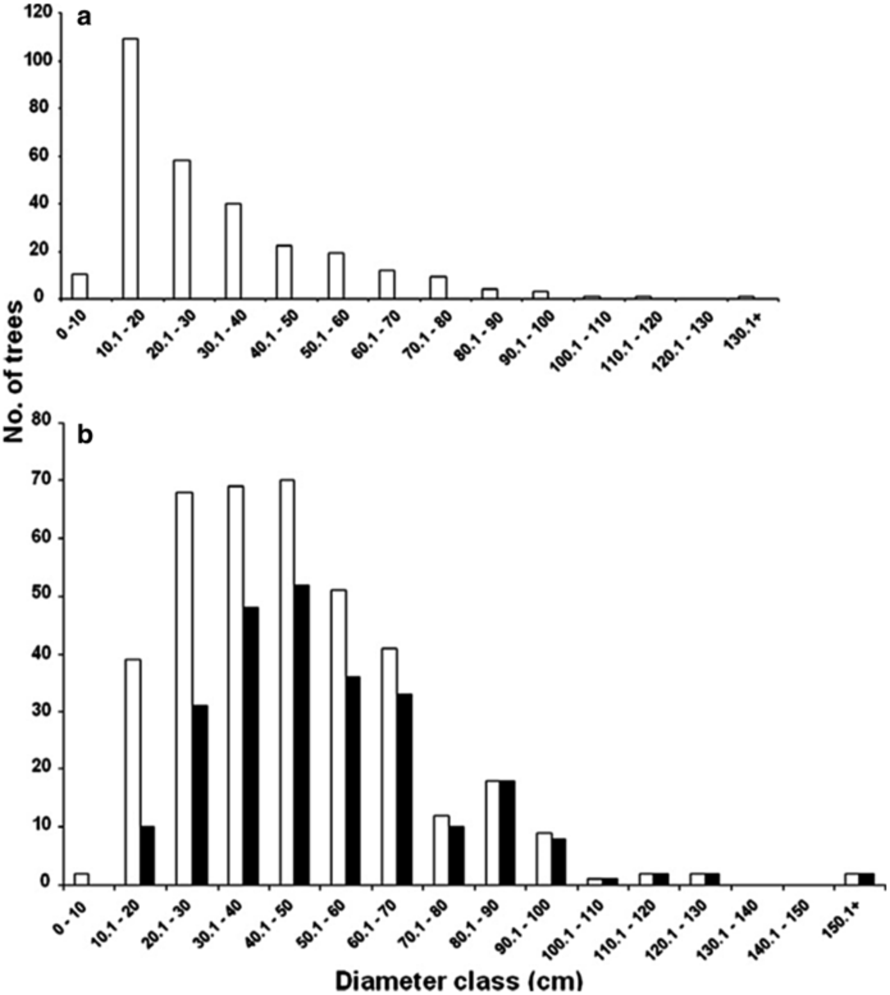

Fig. 22.9 Frequency distribution by diameter of 289 Engelmann oaks, *Quercus engelmannii* (**a**) and 386 coast live oaks, *Q. agrifolia* (**b**) from a survey of a private land parcel (Japatul Valley, California) showing all trees (*open bars*) and trees infested with goldspotted oak borer, *Agrilus auroguttatus* (*black bars*) (Reproduced from Coleman et al. 2012a). Note that none of the *Q. engelmannii* were infested (**a**) and the proportion of infested *Q. agrifolia* increased with diameter class (**b**)

Oak mortality, measured as trees ha^{-1} and basal area (m^2ha^{-1}), associated with *A. auroguttatus* was significantly greater in infested sites of San Diego Co. than uninfested sites in CA, in its native region of AZ, and in native stands of oaks within the distribution of *A. coxalis* in Mexico (Coleman et al. 2012a). The highest rates of mortality attributed to either *A. auroguttatus* or *A. coxalis* was 18 % in AZ, 8 % in Mexico, and 48 % in infested CA sites. In CA, mean oak mortality caused by *A. auroguttatus* was 3.01 (±0.63) and 1.50 (±0.56) trees ha^{-1}, representing 13 % and

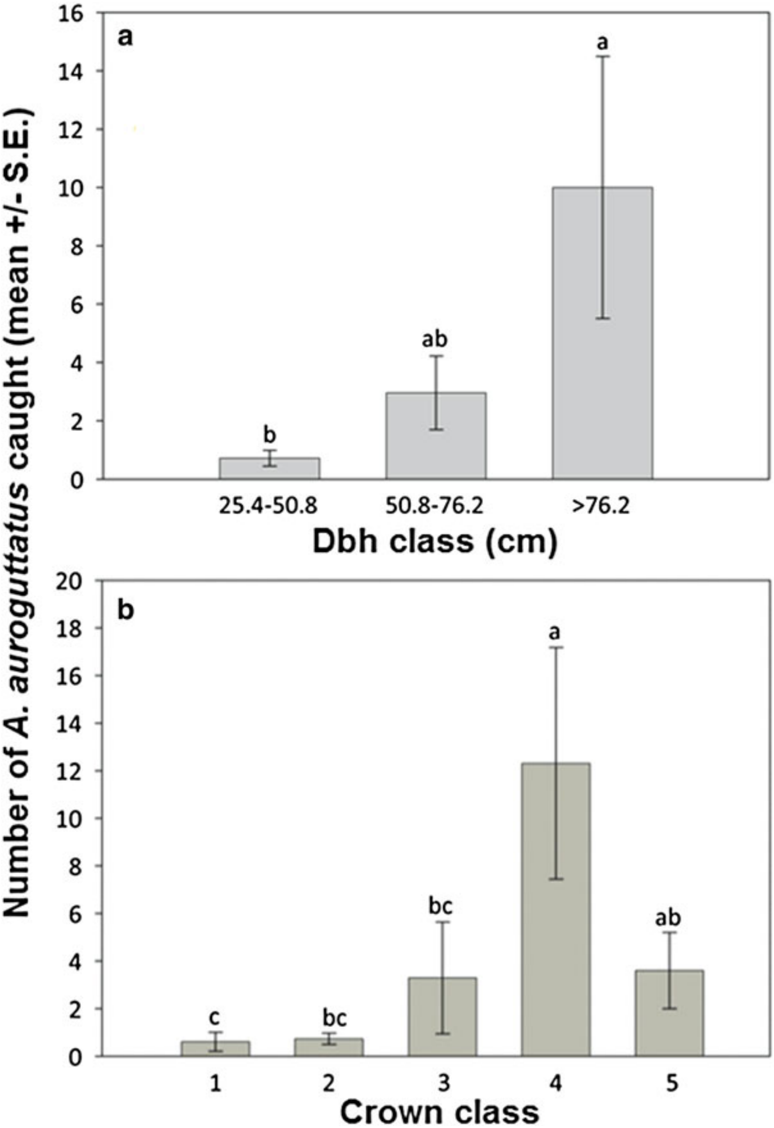

Fig. 22.10 Mean number (±SE) of adult goldspotted oak borer, *Agrilus auroguttatus*, trapped on clear stem panel traps on coast live oaks, *Quercus agrifolia*, across three size classes (**a**) and five crown classes (**b**) in 2010 and 2011, San Diego Co., California (Reproduced from Coleman et al. 2014a). Different lowercase letters above histogram bars within a figure panel indicate significant differences among means (panel **a**: $F_{2,73}=6.13$, $P=0.004$; panel **b**: $F_{4,71}=6.51$, $P=0.001$). Means in panel **a** were calculated (*left* to *right*) based on sample sizes of $N=33$, 26, and 18; means in panel B were calculated (*left* to *right*) based on sample sizes of $N=17$, 21, 21, 13, and 5

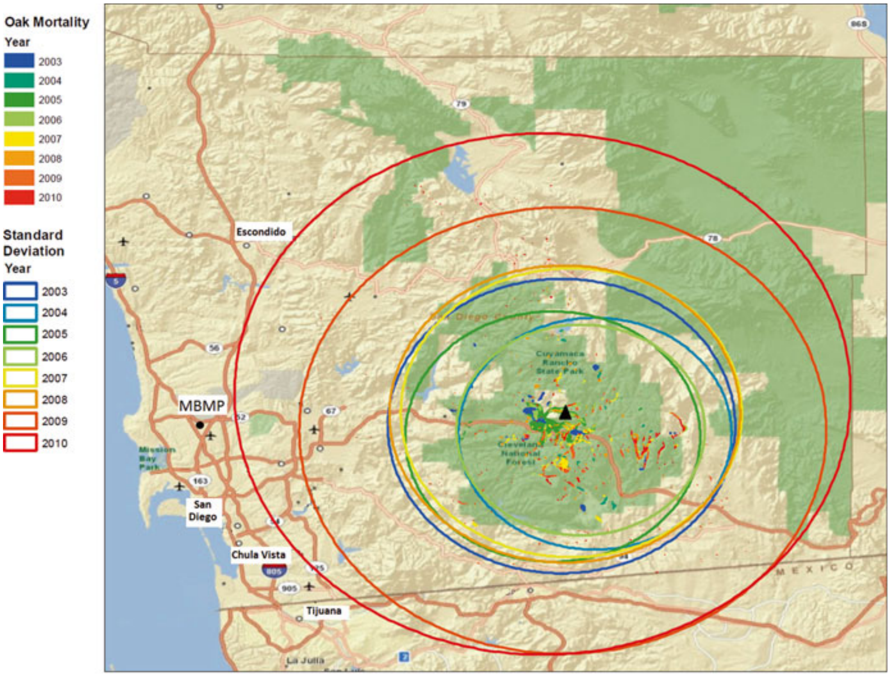

Fig. 22.11 Standard distance analysis of aerial oak mortality polygons (2003–2010) associated with *Agrilus auroguttatus* in San Diego Co., California, USA (Reproduced from Coleman et al. 2012a). The predicted center of oak mortality polygons from 2003 to 2010 is noted in the middle of the geometric means (N). The known satellite infestation in Marian Bear Memorial Park (MBMP) north of urban San Diego is also presented

7 % oak mortality in infested and uninfested sites, respectively. Other studies assessing the impact of *A. auroguttatus* on oak stands in areas where the pest has been present for greater than a decade, report that infestation rates were greater than 80 % and basal killed was greater than 70 % in *Q. agrifolia* and *Q. kelloggii* stands (Coleman, unpublished data).

Oak mortality has continued to accumulate following these initial surveys in San Diego Co. (USDA FHM 2014, Fig. 22.12). From 2012 to 2015, CA experienced a drought that caused increasing water stress to trees throughout the region. In 2014, tree mortality associated with *A. auroguttatus* increased threefold during aerial detection surveys. Oaks killed by *A. auroguttatus* persist in these savannas and woodlands for decades making management options costly due to the numerous reentries required to mitigate safety hazards and reduce fuel loads.

The loss of dominant and co-dominant oaks in savannas, woodlands, and mixed conifer stands and high-value oaks at developed sites (e.g., private residences, parks, campgrounds, trailheads, etc.) has resulted in significant economic and ecological impacts in southern CA. Public and private expenditures and losses have exceeded an estimated $10 million for direct costs and opportunity costs, dead tree mitigation, research, public education/outreach, survey and detection, and lost revenues

Fig. 22.12 Oak mortality (*red stippling*) associated with the goldspotted oak borer, *Agrilus auroguttatus*, in southern California. Satellite infestations in San Diego (San Diego County), Idyllwild (Riverside County), and Orange (Orange County), California are indicated by the names of these communities

(e.g., due to closures of parks and campgrounds for hazard tree mitigation) (GSOB Steering Committee, San Diego Co. 2014). The San Diego Resource Conservation District of Greater San Diego Co. received $3 million dollars from the USDA Forest Service to remove oaks killed by *A. auroguttatus* from private property, reducing the threat of hazard trees and wildfire in and around rural communities.

To date, the secondary ecological impacts associated with elevated tree mortality from *A. auroguttatus* have been poorly studied. These oak savannas and woodlands and mixed conifer stands are habitat for hundreds of species of wildlife, including deer, birds, salamanders, insects, and toads (Pavlik et al. 1996). Habitats of several threatened and endangered species, including the Arroyo toad, *Bufo californicus* Camp (Anura: Bufonidae), are restricted to these oak woodlands with specific requirements of canopy cover or foraging areas provided by *Q. agrifolia* or *Q. kelloggii*. The impact of the loss of the dominant canopy tree species on these wildlife species is not known. Acorns represent an abundant food source for several wildlife species and the loss of this nutritive food source on wildlife populations in these areas is also unknown. The increase of standing dead oaks (snags) may benefit some cavity-nesting birds and the increase of downed woody material may increase habitat for amphibians and rodents, but these impacts have not been studied in San Diego Co. However, the changes in fuel loading structure and composition from extensive oak mortality may influence wildfire behavior in these fire-dominated ecosystems of CA. Preliminary surveys suggest that oak snags still dominate the canopy following >10 years of oak mortality in San Diego Co. and only minimal increases of 1-, 10-, 100-, and 1000-h fuels were recorded on the forest floor (Coleman 2015). Native American tribes of CA have strong cultural ties to these oak woodlands and elevated oak mortality is threatening culturally significant sites and activities, such as pow wows and preparation of native foods. The secondary impacts of *A. auroguttatus* may remain largely understudied for several years because the majority of funding has been directed at developing an integrated pest management program for this new invasive species.

22.9 Community Ecology Centered on *Agrilus auroguttatus*

The absence of aggressive phloem- and wood-boring insects along the main stem of oaks in CA may have represented a relatively vacant *niche* that *A. auroguttatus* has exploited to establish and proliferate in the region (Table 22.1). Like many bark beetles and wood borers, *A. auroguttatus* is found frequently on previously attacked trees (Coleman et al. 2014a; Chen et al. 2015; Haavik et al. 2015), but the beetle will also attack healthy trees in CA (Coleman et al. 2011). Secondary insects are rarely associated with the initial attack of *A. auroguttatus*-infested trees (Flint et al. 2013), and these other subcortical species were found at significantly lower densities on newly killed trees in CA (Haavik et al. 2014a). As tree injury from *A. auroguttatus* has become extensive, these secondary insects have been found more frequently at a later stage of woody biodeterioration throughout the tree (Table 22.1). Western oak bark beetles, *Pseudopityophthorus* spp. Swaine (Coleoptera: Scolytidae), and lead cable borers, *Scobicia declivis* (LeConte) (Coleoptera: Bostrichidae), attack the upper branches of oaks, whereas appletree borers and related species, *Chrysobothris* spp. Eschscholtz (Coleoptera: Buprestidae); oak cordwood borer, *Xylotrechus nauticus* (Mannerheim) (Coleoptera: Cerambycidae); bark and ambrosia beetles (Coleoptera: Scolytidae) e.g., *Xyleborinus saxeseni* (Ratzeburg), *Monarthrum* spp. Kirsch, and *Gnathotrichus pilosus* Wood; and clearwing moths, *Synanthedon resplendens* (Edwards) (Lepidoptera: Sessidae), colonize the main stem (Brown and Eads 1965; Swiecki and Bernhardt 2006; Flint et al. 2013; Coleman et al. 2015). Lynch et al. (2014) report several secondary fungi on oaks in CA that are likely more prevalent on trees due to injury from *A. auroguttatus*.

Interactions of *A. auroguttatus* with native defoliators in CA, such as the western tussock moth, *Orgyia vetusta* Boisduval (Lepidopetra: Erebidae), and California oakworm, *Phryganidia californica* Packard (Lepidoptera: Notodontidae), have not been observed or documented. However, in the eastern USA, defoliation by European gypsy moth, *Lymantria dispar* L. (Lepidopetra: Erebidae) has been noted as a predisposing factor for attack on oaks by the twolined chestnut borer, *A. bilineatus* (Weber) (Haack and Acciavatti 1992), and may serve as a model for interactions between *A. auroguttatus* and the native CA defoliator complex. *Phytophthora ramorum* and *A. auroguttatus* distributions (Grünwald et al. 2012; Coleman et al.

Table 22.1 The entomological context for the goldspotted oak borer, *Agrilus auroguttatus*, invasion of California: bark and wood-boring insects associated with declining oaks and tanoaks[a]

Species	Feeding group	Significance (Early vs. late in decline cycle)
Agrilus auroguttatus[b]	Flatheaded borer, phloem and outer xylem of stem and largest branches	**Highly significant, early**
Coleoptera: Scolytidae		
Pseudopityophthorus pubipennis/ P. agrifoliae	Bark beetles, phloem of stem and branches	Moderately significant, can be early on seriously weakened trees
Monarthrum dentiger/M. scutellare	Ambrosia beetles, xylem of stem and branches	Moderately significant, late – stem breakage of SOD-infected trees
Gnathotrichus pilosus	Ambrosia beetle, xylem of stem and branches	Moderately significant, late – stem breakage of SOD-infected trees
Xyleborinus saxeseni[b]	Ambrosia beetle, xylem of stem and branches	Not significant, late, important for wood decomposition
Cyclorhipidion bodoanum[b]	Ambrosia beetle, xylem of stem and branches	Not significant, late, important for wood decomposition
Coleoptera: Buprestidae		
Chrysobothris femorata/mali /wintu	Flatheaded borers, Pacific flatheaded borer, bark and outer xylem of stem and branches	Not significant, late, important for wood decomposition
Agrilus angelicus	Flatheaded borer, Pacific oak twig girdler, xylem of small branches and twigs	Not significant, early, but attacks peripheral portions of tree
Coleoptera: Bostrichidae		
Scobicia declivis	False powderpost beetle, lead cable borer, xylem of stems and branches	Not significant, late, important for wood decomposition
Coleoptera: Cerambycidae		
Xylotrechus nauticus	Roundheaded borer, oak cordwood borer, phloem and xylem of stem and branches	Moderately significant, can be early on seriously weakened trees
Phymatodes lecontei/ decussatus	Roundheaded borers, phloem and xylem of dying branches/ stem	Moderately significant, can be early on seriously weakened trees
Neoclytus conjunctus	Roundheaded borer, phloem and xylem of dying branches/stem	Moderately significant, can be early on seriously weakened trees

[a] Brown and Eads (1965); Furniss and Carolin (1977); Swiecki and Bernhardt (2006); McPherson et al. (2008); Coleman and Seybold (2008b, 2011); Kelsey et al. (2013); and Beh et al. (2014)

[b] Invasive species

2015) currently do not overlap in CA, but the potential interaction of these two exotic species threatens native oak stands along CA's Central Coast. *Phytophthora ramorum* appears to be spreading faster in a northern direction along the moister, coastal areas of CA and Oregon (OR) than to the drier regions of southern CA (Grünwald et al. 2012; Kanaskie et al. 2013; USDA FHM 2014). The distributions of the polyphagous shot hole borer, *Euwallacea* nr. *fornicatus* (Eichhoff) (Coleoptera: Scolytidae), a new exotic ambrosia beetle to CA (Coleman et al. 2013), and *A. auroguttatus* do overlap in San Diego Co. However, preliminary surveys suggest that *E.* nr. *fornicatus* does not favor oaks and the two exotic species infrequently attack the same trees (Coleman, unpublished data 2015).

In addition to *A. auroguttatus*, *E.* nr. *fornicatus*, and *P. ramorum*, there are a few other potential exotic threats to oak ecosystems in CA. There are at least 42 species of *Agrilus* associated with oaks in North America (Nelson et al. 2008; Haack et al. 2009; Petrice and Haack 2014), but here are two species in the eastern half of the North American continent that may threaten CA. One of these is native and quite damaging (*A. bilineatus*, Haack and Acciavatti 1992), whereas the other is from Europe (*A. sulcicollis* Lacordaire, Petrice and Haack 2014). Both of these species colonize both white and red oaks; *A. sulcicollis* appears to utilize oaks that are in a more advanced state of biodeterioration and no direct oak mortality has been ascribed to this species in eastern North America (Petrice and Haack 2014). However, in Europe, *A. sulcicollis* has been considered amongst a complex of *Agrilus* sp. to have been associated with oak decline (Moraal and Hilszczański 2000; Evans et al. 2004; Hilszczański and Sierpinski 2007). Another member of this complex that may be even more damaging to CA oaks is *A. biguttatus* (Moraal and Hilszczański 2000; Vansteenkiste et al. 2004; Davis et al. 2005a; Brown et al. 2015). This species has demonstrated that it can expand its range (Pederson and Jørum 2009) and appears to have markedly increased its population density and distribution in Britain (Brown et al. 2015). The life history, habits, and impact of *A. biguttatus* in Europe seem to be quite similar to those of *A. auroguttatus* in CA (Brown et al. 2015). Other potentially invasive forest insects that may exert stress on oaks in CA include another flatheaded borer, the black-banded oak borer, Coraebus florentinus (Herbst) (Jurc et al. 2009; Sallé et al. 2014); a relatively aggressive bark beetle, Scolytus intricatus (Ratzeburg) (Jurc et al. 2009, Sallé et al. 2014); and the aforementioned *L. dispar* and related erebids (formerly lymantriids) from Eurasia (Gninenko and Gninenko 2002; Davis et al. 2005b).

22.10 Management of *Agrilus auroguttatus*

Components of an integrated pest management (IPM) program have been developed, or assessed, to prevent tree mortality from *A. auroguttatus* in CA (Coleman et al. 2009; Coleman et al. 2015; Seybold and Coleman 2015). This program includes tools for monitoring *A. auroguttatus*, managing infested wood, preventing attack through insecticide applications, and assessing options for classical or augmentative biological control. Future research should synthesize all aspects of these tools to prevent elevated levels of tree mortality at a site and to maintain management objectives.

Ground surveys are an effective means for identifying *A. auroguttatus*-infested trees as a consequence of the tendency for *A. auroguttatus* to oviposit on the lower parts of the main stem, thus allowing trees of all infestation levels to be identified (Coleman et al. 2011; Hishinuma et al. 2011). Large-diameter red oaks are the preferred host and should be the focus of ground surveys in which infested trees are ranked according to the degree of injury from *A. auroguttatus* (Hishinuma et al. 2011). However, these ground surveys are time consuming, can be limited in scope, and require trained technicians.

Monitoring techniques for *A. auroguttatus* based on flight trapping are not very sensitive. Purple and green prism flight-intercept traps (three-sided, 35.6 by 59.7 cm) developed for monitoring *A. planipennis* (Francese et al. 2008) were more effective at catching adults of *A. auroguttatus* when compared to other trap types (Coleman and Seybold 2008b). Purple and green flight-intercept prism traps were equally effective at catching *A. auroguttatus* males, but purple traps caught more females than green traps (Coleman et al. 2014a). When purple and green traps were hung at 3.0 m, significantly more adults of both sexes were caught on the purple traps. Traps hung at 4.5 m caught significantly more *A. auroguttatus* females than traps placed at 1.5 m. Males did not respond differently to prism traps hung at 1.5, 3.0, and 4.5 m. The addition of Manuka oil [i.e., the steam distillate of the manuka tree (New Zealand teatree), *Leptospermum scoparium* J.R.Forst. & G.Forst.], Phoebe oil (i.e., the steam distillate of the Brazilian walnut tree, *Ocotea porosa* (Nees & Martius) Barroso, and the green leaf volatile (3*Z*)-hexenol did increase trap catch of *A. auroguttatus* males on green and purple prism traps hung at 3.0 m (Coleman et al. 2014a). Additional laboratory (e.g., electroantennographic detection assays) and field studies have assessed the potential effectiveness of oak volatiles as an attractant for *A. auroguttatus*. Oak volatiles have been sampled from stressed and uninfested and *A. auroguttatus*-infested *Q. agrifolia*, but none have been effective for monitoring *A. auroguttatus* populations. Clear sticky coated panel traps (37.5 × 25 cm, Tanglefoot Company, Grand Rapids, MI, USA) affixed to the main stem of oaks at breast height were effective for monitoring the landing rates of *A. auroguttatus* (Coleman et al. 2014a). Clear sticky panel traps may be useful for monitoring *A. auroguttatus* populations in management actions at high-value sites.

Adult flight for *A. auroguttatus* detected with purple prism traps or clear sticky panel traps hung on the bole of infested trees began in late May and ended by early September over a several year period (reviewed in Coleman et al. 2014a). Coleman and Seybold (2008b) and Haavik et al. (2013) recorded seasonal flight patterns for *A. auroguttatus* and found activity as late as early November and October, respectively. Peak adult flight for *A. auroguttatus* across a range of elevations in southern CA occurs primarily from late June to early July (Coleman et al. 2014a). Emergence data from infested firewood-sized pieces of *Q. agrifolia* in the field support these general seasonal trends in flight activity for *A. auroguttatus* (Jones et al. 2013).

Research on monitoring *A. auroguttatus* with flight trapping has led so far to the use of the unbaited purple prism flight-intercept trap as the primary tool. These traps (hung at 3 m) have been used to delimit the distribution of *A. auroguttatus* in native oak woodlands and at high-value sites in CA (Coleman et al. 2014a). Traps are typically installed in late May and monitored until early September to coincide with our knowledge of adult flight activity. The traps are recommended solely as a monitoring tool and are not effective for preventing or suppressing infestations. As has been demonstrated for other species of buprestids, additional research on responses to host volatiles (Silk et al. 2011; Fürstenau et al. 2012), and to visual (Domingue et al. 2011, 2013a, b) and/or olfactory (Crook and Mastro 2010; Silk et al. 2009, 2011; Fürstenau et al. 2012; Ryall et al. 2012, 2013) signals from conspecifics may be merited with *A. auroguttatus*.

Movement of infested wood was likely the pathway for the introduction of *A. auroguttatus* into CA and was responsible for the establishment of the Orange, Riverside, and Los Angeles Cos. satellite infestations in southern CA, as well as several major range expansions in San Diego Co. (Marion Bear and Heise Parks). Education and outreach programs have sought to limit the movement of infested wood since no quarantines or restrictions were established for *A. auroguttatus* in CA. Grinding infested wood to a particle size of <7.62 cm was effective at killing *A. auroguttatus* in trials (Jones et al. 2013, Fig. 22.13); however, this management option is often restricted to large-scale management operations due to the cost of the specialized equipment required. Solarizing infested wood with clear plastic sheeting did not prevent emergence of *A. auroguttatus*, but did restrict the dispersal of the adults that may eventually cause tree mortality (Jones et al. 2013). Removing the bark and phloem from infested wood pieces (=debarking) can separate *A. auroguttatus* from the wood, but the bark and phloem can still harbor viable populations (Jones et al. 2013). Debarking is restricted to small quantities of wood because this option is very labor intensive. However, this technique does preserve the integrity of the firewood pieces for sale or use.

Application of contact insecticides to the main stem and larger branches (20.3 cm in diameter) of high-value red oaks may prevent tree mortality from this exotic species. Carbaryl (carbamate), bifenthrin, lambda-cyhalothrin, and permethrin (all pyrethroids) have killed *A. auroguttatus* adults and reduced adult feeding in laboratory no-choice leaf-feeding bioassays 1 and 12 months post-application (Coleman et al. 2015). Contact treatments should be applied once a year in May and applied only to uninfested trees or trees with only low levels of injury from *A. auroguttatus*. Insecticides should not be applied to GSOB-infested oaks with a crown injury ranking of "3" or greater and an emergence hole ranking of "3" (>25 emergence holes) (Hishinuma et al. 2011) because they have already experienced high levels of injury and are not likely to recover.

Systemic insecticides applied as a trunk injection have been the most promising treatment for preventing attack and mortality from *A. auroguttatus*. Applications of emamectin benzoate or imidacloprid have been made experimentally from December to February in southern CA (when precipitation is most likely) (Chen et al. 2015; Coleman et al. 2015). In no-choice leaf-feeding bioassays with *Q. agrifolia* and *Q. kelloggii*, emamectin benzoate and imidacloprid significantly reduced adult *A. auroguttatus* feeding and survival (Coleman et al. 2015). Residues of imidacloprid were detected at high levels (17 μg/g) in foliage 2 years post-application. Chen et al. (2015) reported that emamectin benzoate-injected trees had reduced annual increases in the appearance of *A. auroguttatus* emergence holes when compared to untreated

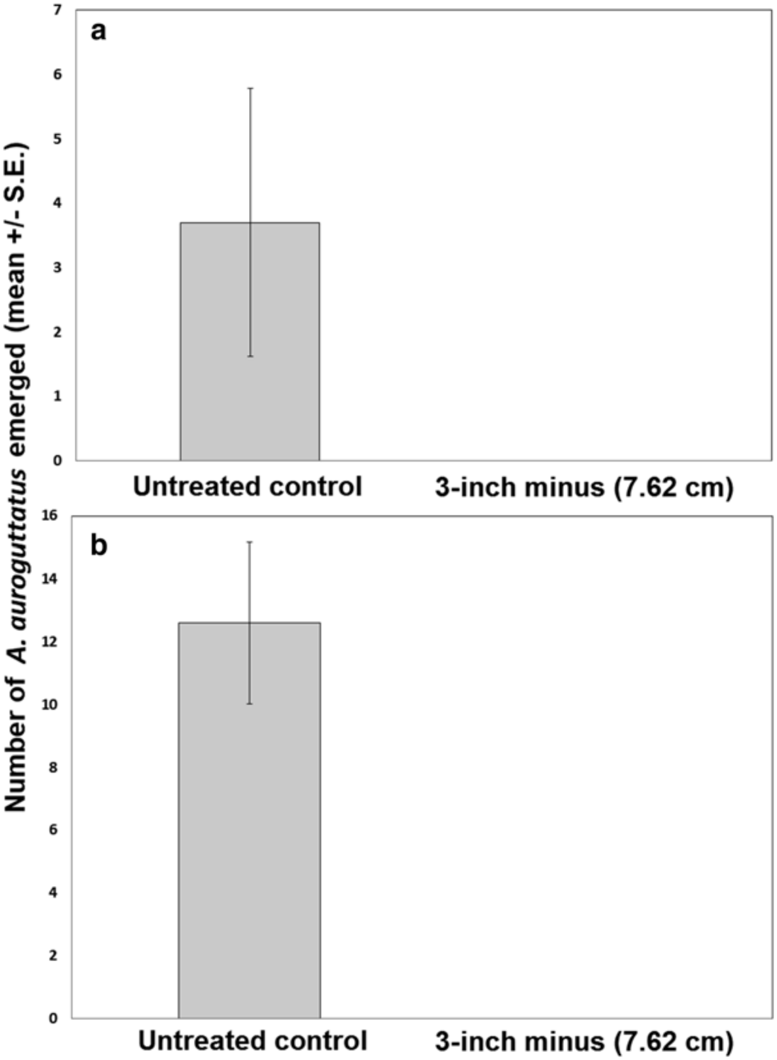

Fig. 22.13 Mean (±S.E.) emergence of adult goldspotted oak borer, *Agrilus auroguttatus*, following grinding infested coast live oak, *Quercus agrifolia*, firewood to a 3 inch-minus (7.62 cm) piece size in 2010 (panel **a**: $F1,12=22.2$, $P<0.001$) and 2011 (panel **b**: $F1,12=103$, $P<0.001$) in southern California (Reproduced from Jones et al. 2013)

trees. This suggests that larvae of *A. auroguttatus* may be impacted by the treatment. In the same study, imidacloprid-injected trees had significantly lower annual increases in emergence holes 1.5 and 2.5 years after the treatment (Chen et al. 2015). Stem injections of emamectin benzoate and imidacloprid should be reapplied during the dormant months once every 2 years until additional data is collected. Applications of dinotefuran (a neonicotinoid) did not reduce beetle feeding or survival in no-choice leaf-feeding bioassays, but residues were highest (3 μg/g) 2 weeks following application in the foliage when bioassays were conducted (Coleman et al. 2015). However, residues of dinotefuran declined drastically 5 months post-application and should be reapplied to trees every year at the first of June to coincide with the peak adult flight period.

Large diameter moderately- and severely-infested trees (i.e., "brood" trees) are unlikely to be saved by insecticide treatment and will likely die in a few years. At newly infested sites, these trees may contain 66–93 % of the *A. auroguttatus* population density in an oak woodland (Haavik et al. 2015). As a result, these brood trees should be felled and the wood handled and processed properly to potentially reduce the local population. This management option (e.g., removal of large diameter moderately- and severely-infested trees) has been assessed at several satellite infestations in high-value settings in CA, but no data are currently available to support recommendation of this approach.

Natural enemies may contribute to controlling populations in its native region, but other biotic factors may also be involved (e.g., host resistance). *Calosota elongata* Gibson (Hymenoptera: Eupelmidae), a newly described ectoparasitoid wasp (Gibson 2010), was discovered killing *A. auroguttatus* prepuae in AZ (Coleman and Seybold 2011; Coleman et al. 2012b, Fig. 22.14). The parasitoid has never been found attacking other species, but little is known about this new species of wasp. *Calosota elongata* was later found in the *A. auroguttatus*-infested areas of CA, and was likely introduced with the original population of *A. auroguttatus* (Haavik et al. 2012a). A *Trichogramma* sp. wasp (Hymenoptera: Trichogrammatidae) was found parasitizing GSOB eggs in AZ, but it is believed to be a generalist parasitoid (Lopez and Hoddle 2013). Other generalist predators and parasitoids, including the straw itch mite, *Pyemotes tritici* Lagrèze-Fossat and Montané (Acari: Pyemotidae), *Atanycolus simplex* (Hymenoptera: Braconidae), snakeflies (Raphidioptera), and bark-gnawing beetles (Trogossitidae), have been associated with *A. auroguttatus* in its native or introduced regions (Coleman and Seybold 2011; Coleman et al. 2014b, 2015). The impact of these parasitoid and predators on *A. auroguttatus* populations is unknown in AZ and CA. Classical and augmentative biological control will likely not be effective for *A. auroguttatus* in CA despite the discovery of several parasitoids and predators in AZ, CA, and Mexico (Lopez et al. 2014a; Coleman et al. 2015). Hurdles encountered when rearing *A. auroguttatus* on cut logs and the difficulty of rearing high densities in a laboratory setting make biological control infeasible at this time.

22.11 Risk of *Agrilus auroguttatus* in the United States of America and Potential for Introduction to Other Forest Ecosystems

A risk assessment model was developed for *A. auroguttatus* primarily in the USA and based on climate suitability and various biological factors: mean temperature during the warmest quarter; total rainfall during the driest month; cold tolerance

Fig. 22.14 Larvae of *Calosota elongata* (Hymenoptera: Eupelmidae) feeding on a larva of the goldspotted oak borer, *Agrilus auroguttatus*, in the phloem of Emory oak, *Quercus emoryi*. Specimens were photographed on the Coronado National Forest in southeastern Arizona

(e.g., supercooling point for mature prepupae); host range; and adult flight distance (Venette et al. 2015, Fig. 22.15). The highest risk of establishment for *A. auroguttatus* was predicted throughout CA along the Coastal Mountain Range and the foothills of the Sierra Nevada Mountain Range and into southwestern Oregon. Additional risk was predicted in its native region of southeastern AZ and southwestern New Mexico and in Baja California Norte, Mexico. The risk model was based on natural dispersal and in 2022 its northern distribution is predicted to be along the Transverse Mountain Ranges in southern CA. The model did not account for spread and punctuated discontinuities in the invaded range *via* the movement of infested firewood, which was likely responsible for several satellite infestations in San Diego and introductions into Riverside (2012), Orange (2014), and Los Angeles (2015) Cos. The introduction of *A. auroguttatus* in Orange Co. (discovered in December 2014) and Los Angeles Co. (discovered in August 2015) surpasses the 2016 predicted range in the model; again, suggesting that human-assisted dispersal may have been the source for the original introduction to CA. No risk of establishment was predicted for *A. auroguttatus* in the eastern USA using these parameters. It is also unknown how *A. auroguttatus* may interact with *L. dispar*, *A. bilineatus*, other wood-boring species, and their associated natural enemies in this eastern region. The model describes no risk of *A. auroguttatus* for this region.

A lumber market does not exist for oaks killed by *A. auroguttatus* in CA; most dead or dying oaks are converted to wood for heating. The revenue gained for selling oak firewood far exceeds the cost benefits for utilizing and processing this wood for other means (e.g., mulch, biofilters for water treatment facilities, high-end lumber markets).

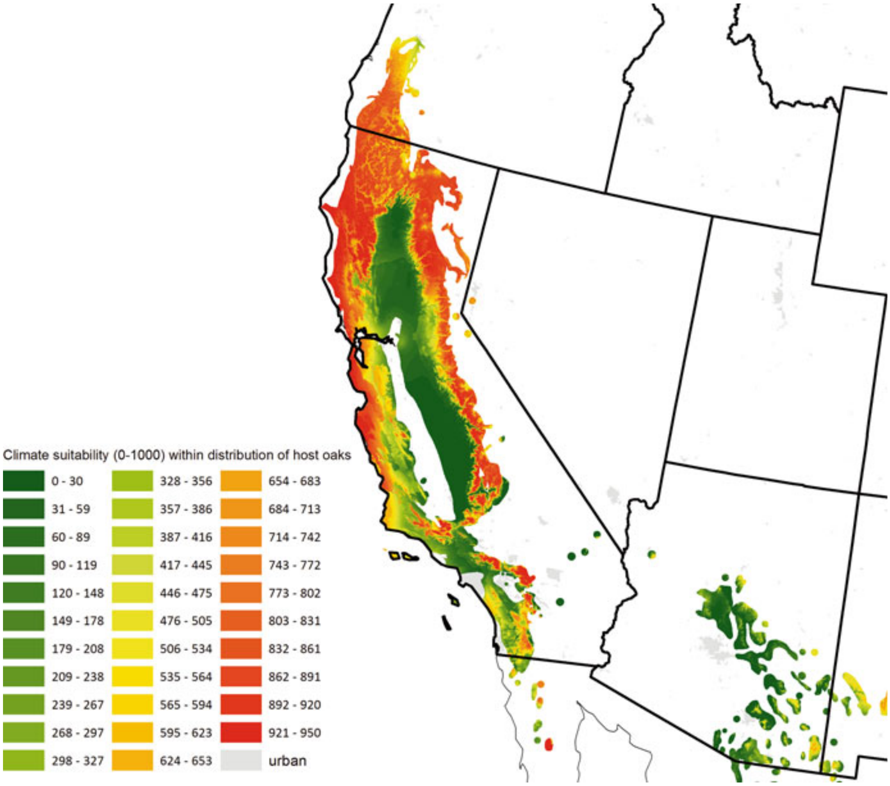

Fig. 22.15 Risk to oak resources from the goldspotted oak borer, *Agrilus auroguttatus*, in the western USA and Baja California Norte, Mexico. The risk map is based on the host distributions and climate suitability for *A. auroguttatus* as determined by laboratory host range tests and the distribution of historical collection records in southeastern Arizona and the invaded range in southern California (Reproduced from Venette et al. 2015)

However, the cost of moving large quantities of firewood is not cost effective over long distances. Satellite introductions in CA have likely resulted from small quantities of wood (e.g., a pick-up truck load). *Agrilus auroguttatus* does not frequently attack smaller diameter oaks (<12.5 cm dbh), so the risk of moving this species *via* nursery stock is not likely. Thus, the spread of *A. auroguttatus* to other Mediterranean countries is not likely either *via* the movement of lumber products, infested firewood, or ornamental trees.

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