Mapping spread of the Goldspotted Oak Borer (*Agrilus auroguttatus*)[1]

Thomas A. Scott,[2,3,4] Kevin Turner,[3,4] Cara Washington,[4] and Kim Corella[5]

Abstract

The earliest signs of goldspotted oak borer (*Agrilus auroguttatus*, GSOB)-associated oak declines can be found in 1996 aerial photo images from the Descanso area of San Diego County. By 2014, GSOB had spread over a 4000 km^2 area, with a patchy distribution similar to the early spread of the emerald ash borer (*Agrilus planipennis*). The GSOB occurs over about 26,250 ha (60 percent) of the oak woodlands in its primary range of infestation; with heaviest damage near rural housing and communities. Three GSOB diaspora have occurred 30, 40, and 55 km from closest known infestation areas, implicating human transport rather than adult flight as the agent of dispersal. Sequential aerial photo plots suggest that individual oaks (7916) took a median of 3 years to die after first sign of canopy decline, and 95 percent died within 8 years. Plots with >9 years of GSOB attack lost up to 76 percent of their oak canopies, with up to 25 percent of canopy loss/year in drought years. Oak canopy losses averaged about 3 percent of total area/year, or the equivalent of about four large, mature oak trees/ha/year. Years of high precipitation slowed GSOB mortality, followed by rapid increases in mortality when these years were followed by a drought year.

Key words: *Agrilus auroguttatus*, forest pest, goldspotted oak borer, GSOB, oak management, oak woodlands, *Quercus agrifolia*, *Quercus chrysolepis*, *Quercus kelloggii*

Introduction

Oak mortality in San Diego County rapidly increased in the fall of 2002, the fourth year of a 5-year drought. Although this increase resembled previous waves of mortality seen in multi-year droughts (1974-1978 and 1988-1990), higher rates of oak mortality did not stop after a season of heavy precipitation in 2005. The extent of this mortality was initially masked by two large wildfires in 2003 and 2007 (CALFIRE 2014); however, by 2008 an unprecedented number of unburned oaks were reported as dead or in irreparable decline across a large section of the county. In that year, Seybold and Coleman (2008) linked this oak mortality to an outbreak of the goldspotted oak borer (*Agrilus auroguttatus*, hereafter referred to as GSOB), an exotic bark beetle from the Sierra Madre Occidental (Mexico) and the sky islands of southeast Arizona (Lopez 2015). The first adult GSOB was trapped in San Diego County by the California Department of Food and Agriculture in 2004 (Westcott 2005), but increased rates of oak mortality had been observed 2 years before (Heath and others 2008). We began mapping areas where oak mortality exceeded background levels (1 dead/1000 mature per year) in 2007, and extended our mapping

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[2] Department of Environmental Science, Policy, and Management, University of California, Berkeley, CA 94720.
[3] Department of Earth Sciences, University of California, Riverside, CA 92521.
[4] University of California Cooperative Extension.
[5] California Department of Forestry and Fire Protection. 635 N. Santa Rosa, San Luis Obispo, CA 93405.

area to the entire county as the extent of GSOB damage became evident. In 2009 we set up sequential aerial photo plots to reconstruct the early pattern of GSOB spread.

Methods

Mapping susceptible-oak woodlands and GSOB occurrence

Oak woodlands in San Diego and Riverside Counties have been mapped by Wieslander (1935; see vtm.berkeley.edu), Griffin and Critchfield (1972), Oberbauer (unpublished 1987), Scott (1991), Anon. (1995), California Department of Fish and Game (2005), U.S. Department of Agriculture Forest Service (USDA FS) CALVEG 2002, 2003, 2009 (USDA FS Region 5 2014), and R. Minnich (unpublished MS). These maps identified the distributional range of the woodland types with susceptible oak species, but with classification systems that mixed oaks with other vegetation, at map scales too coarse (>1:24000) to describe spread. We refined the woodland polygons in these maps to produce a map of susceptible oak woodland canopies at a scale of approximately 1:1500, using georeferenced (in ARCGIS©) satellite and aerial photo imagery to draw canopy boundaries (Eagle Aerial Imaging from 2003-2006, 2008, 2009, 2010; Google Earth Imagery 2010, 2012, 2013, 2014; with pixel size from 0.5 to 1 m). We included woodlands with California black oak (*Quercus kelloggii*), coast live oak (*Q. agrifolia*), canyon live oak (*Q. chrysolepis*), interior live oak (*Q. wislizenii*), and Engelmann oak (*Q. engelmannii*). Our goal was to map just the susceptible-oak trees canopies, minimizing the inclusion of non-canopy habitat and other vegetation types. In woodlands with >75 percent canopy cover, we mapped polygons by canopy perimeters; in woodlands with 20 to 75 percent canopy cover we excluded gaps >150 m^2 (equivalent to canopy of a two mature oaks) from canopy polygons. In woodlands with <10 percent canopy cover, we attempted to map individual oak canopies.

We classified canopy polygons into five mortality levels, based on counts of dead oak canopies per unit area. Categories with known presence of GSOB and mortality were classified as (1) **Heavy**, >10 dead oaks/ha of canopy; (2) **Moderate**, 5 to 10 dead oaks/ha; and (3) **Present**, 2 to 5 dead oaks/ha. Whenever possible, we ground-verified the presence of GSOB in canopy polygons by field surveys (2008-2014). In addition, we mapped GSOB locations identified by professional foresters, resource managers, arborists, scientists, and trained volunteers. We used two additional categories when GSOB presence could not be checked on the ground (private property): (1) **Probable**, with 1 to 2 dead oak/ha) and **Possible**, 0.5 to 1 dead oak/ha).

Describing the onset and rate of GSOB outbreaks

We estimated the onset and rate of GSOB utbreaks across the infestation area using sequential aerial photo images. Our goal was to use woodland sample units with a median size of 25 ha oaks; to reflect the scale of the outbreaks with a sufficient number of oaks (300 to 500) to describe patterns of GSOB-associated mortality. Oak woodlands in the GSOB infestation area typically occur in distinct patches; we randomly selected 75 of these patches from our oak woodland map to sample oak mortality across the region where GSOB occurred. Sampling was stratified by elevation, drainage basins, woodland type, size, and geographic location (nearest-neighbor distance >2 km). For each woodland sample unit, we digitized all oak canopy areas that could be resolved at a scale of 1:1500, 1m pixel size across a sequential series of aerial photo images, 2002 through 2013, from Google Earth (2002-2013), Eagle Aerial Imaging (2003-2006, 2008, 2009, 2010), USDA NAIP (2009, 2012), USGS Digital Orthophoto Quadrangles (DOQs, 1996, 2005) coverages of San Diego County. Each year's image was georeferenced to the 2009 NAIP (NAIP 2010; NAD1983 UTM Zone 11N) image for San Diego County (>five control points; root mean square errors (RMS) of control points <0.5, median of RMS value of 0.2). We mapped canopies of five species: California black oak, coast live oak, canyon live oak, interior live oak, and Engelmann oak. Oak canopies in each year were digitized as polygons in ArcGIS (ESRI versions 9.3 and 10.2.2), decline in the canopies of individual oak tree were detected by recording change in canopy color, pattern and outline; death was recorded when a canopy was reduced to bare branches, trunk, or stump. We scaled canopy change/decline as typical, declining, irreparably declining, or dead. To document the spread of GSOB among plots, we recorded the year when individual canopy areas changed from typical to irreparable decline (>50 percent canopy decline), or from typical, declining, or irreparably declining to dead . To calculate total canopy loss per woodland, we set the canopy area (m^2) of individual oaks in 1996 USGS DOQs as the initial condition, subtracting canopy lost/year. We then compared this rate of loss against background mortality calculated from canopy area lost in samples where GSOB did not occur.

Results and discussion

Range and distribution of GSOB

By the fall of 2014, GSOB had been associated with oak mortality on approximately 26,250 ha (66,700 ac) of oak woodlands in San Diego County, with an additional 9600 ha (24,400 ac) in transition to or likely to be affected in the near future. The range of GSOB-affected woodlands extends from the borderlands of Mexico to the southern end of the Palomar Mountains, and from the desert margin to coastal woodlands near sea level (fig. 1).

In total, the primary GSOB infestation area encompasses about 43,500 ha of oak-associated woodlands. This range also includes about 8900 ha of woodlands burned in the 2003 Harris Fire and the 2007 Witch Fire (CALFIRE 2014), where it was impossible to separate GSOB-associated oak mortality from the extensive oak mortality resulting from fire. These fires occurred after GSOB mortality began, removing evidence of an additional 34 percent of GSOB-impacted woodlands. The oldest areas of infestation have the most contiguous outbreak polygons, newer areas of infestation have a far patchier pattern of outbreak with intervening areas where GSOB has not been detected.

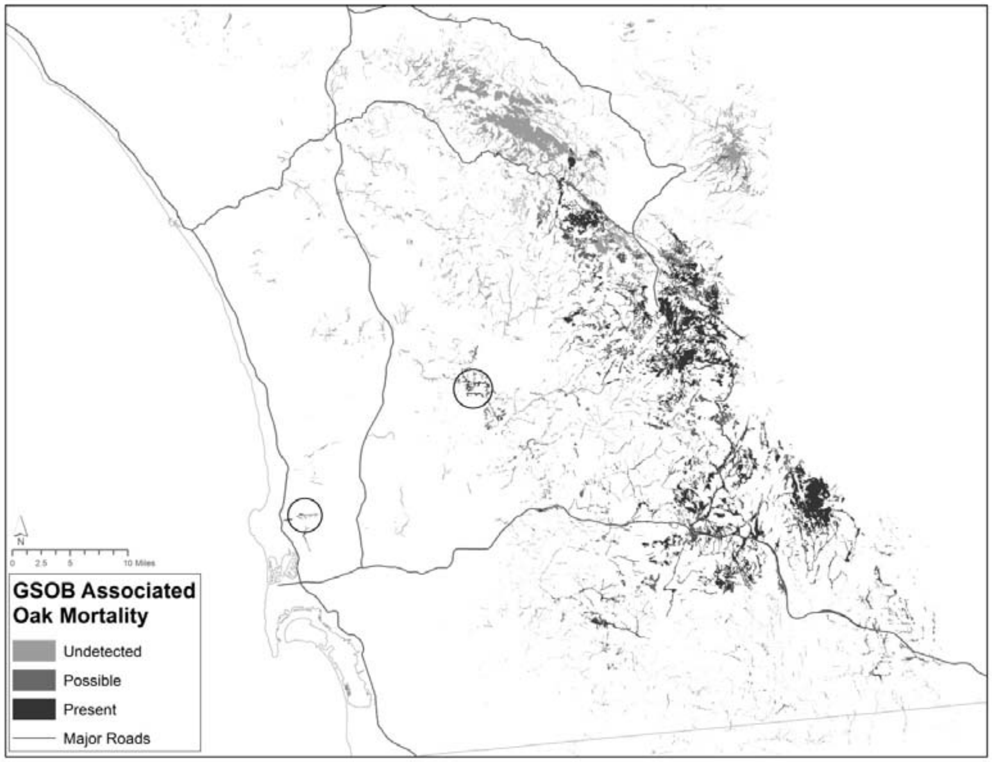

Figure 1—Map of San Diego County showing the fall 2014 distribution of goldspotted oak borer (*Agrilus auroguttatus*) (mortality categories defined in the methods section). Extreme examples of isolated outbreaks (circled) were most likely caused by human transport of GSOB. The Idyllwild outbreak area is not included to maximize detail of the map in the primary infestation area.

Three separate diaspora of GSOB have been recorded, where beetles moved further than the adult flight limit estimated by Lopez (2013). These new, isolated points of infestation occurred at Marion Bear Park (40 km, before 2008), Ramona (30 km in 2007), and Idyllwild (55 km around 2009). Surveys for GSOB in these remote infestations initially found about 100 ha of infested coast live oak woodlands at Marion Bear Park, 250 ha of similar woodlands infested in Ramona, and 700 ha of infested California black oak woodlands in the Idyllwild. Large tracts of woodlands free of GSOB infestation occur between these isolated outbreaks and the primary infestation area; leaving human transport as the most parsimonious explanation of these GSOB movements. The Idyllwild outbreak represents a special case because there may have been more than one delivery of GSOB-infested oak firewood, creating a constellation of small outbreaks across that community (Turner 2015). There are about 17 300 ha of unaffected oak woodlands in patches across the GSOB the zone of infestation, reflecting both the duration of the outbreak and the unpredictable nature of GSOB movement in firewood. At present, there is little evidence to suggest that the spread of GSOB varies significantly from the early pattern of spread described by Siegert and others (2014) for the outbreak of emerald ash borer.

Woodlands with California black oaks had the highest proportions of heavily infested woodland areas, while canyon-bottom woodlands had low proportions of GSOB outbreak areas (fig. 2). Heaviest GSOB impacts occur in woodlands types at higher elevations (fig. 3). Canyon woodlands are dominated by coast live oak, a highly susceptible species; however, a substantial proposition of their distribution is outside of the GSOB-infestation area (fig. 3). Engelmann oak-dominated woodlands have a high percentage (58 percent) of area with GSOB present, but a relatively low percentage of area with heavy GSOB impacts. The presence of GSOB is expected because this woodland type occurs almost entirely within the GSOB-infestation area; however, the lack of commensurate levels of heavy to moderate infestations are function of the low percentage of susceptible species (0 to 25 percent) in Engelmann oak dominated woodlands (Scott 1993).

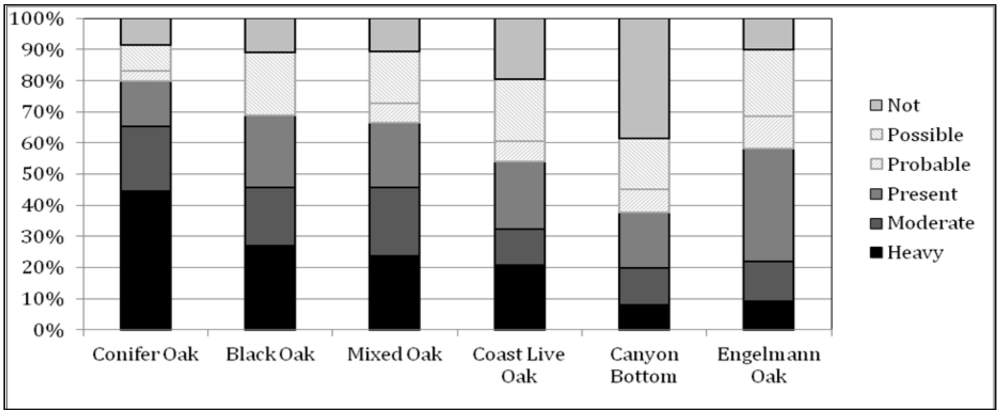

Figure 2—Intensity of GSOB damage by woodland type. The greatest GSOB-associated damage has occurred in woodlands with California black oak, *Quercus kelloggi* (first three columns).

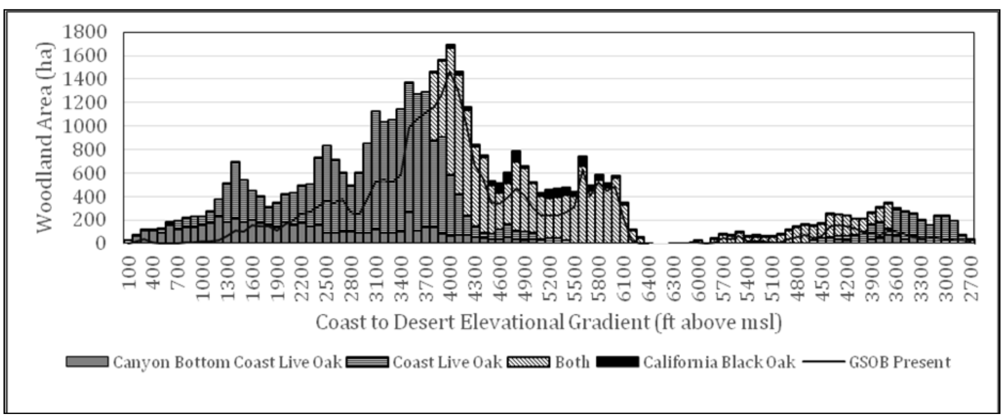

Figure 3—Distribution of GSOB across elevational gradients of the two most susceptible species, coast live oak (*Quercus agrifolia*) and California black oak (*Q. kelloggii*). Oaks occur from coastal lowlands (far left) to the trans-montane desert (right).

There is a strong elevational gradient of GSOB damage, which are concentrated above 930 m (3100 ft) above mean sea level (amsl) (figs. 3 and 4) and uncommon below 870 m (1600 ft) (fig. 4). Lower elevation areas have remained remarkably free of GSOB damage even though they receive less precipitation and should be subject to greater stress and susceptibility to GSOB during droughts. The highest prevalence of GSOB outbreaks occur between from 1020 to 1290 m (3400 to 4300 ft). These elevations have large areas of oak woodlands, but they also have large number of rural houses and the greatest likelihood of firewood importation for heating (fig. 4).

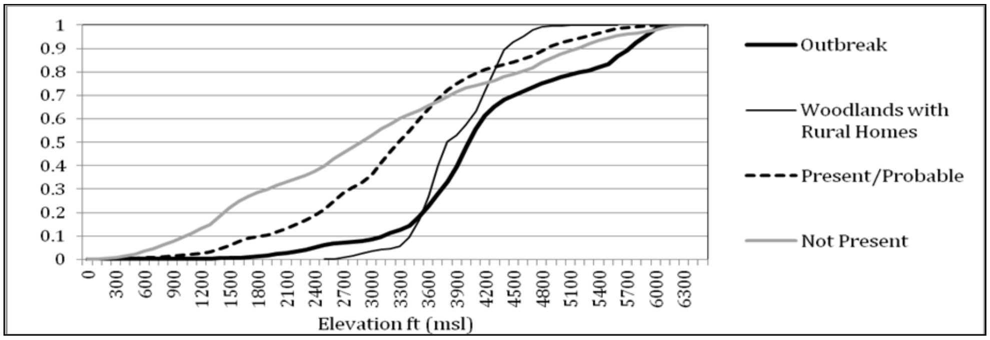

Figure 4—Cumulative frequency distribution of GSOB-associated oak mortality along an elevational gradient. Ninety percent of woodlands with moderate to heavy GSOB-associated mortality (= Outbreak) were above 1050 m (3100 ft) elevation. The elevational distribution of this outbreak is almost indistinguishable from the elevational distribution of woodlands within 100 m of rural homes. Both of these distributions however differ significantly from the cumulative elevational distribution of woodlands where GSOB is not present (Kolmogorov-Smirnov 2 sample test. P <0.01).

Rural homes are a strong indicator of GSOB outbreaks, and an indirect link to GSOB import of firewood for heating in higher elevation areas of San Diego County. Woodlands next to rural homes have a far greater prevalent of moderate- to heavily-attacked oak woodlands, and have a far lower prevalence of unaffected oaks. About 33 percent of woodlands within 100 m radius of rural houses were heavily impacted by GSOB in 2014 (fig. 5), close to twice the percentage (17.5 percent) of heavily damaged woodlands beyond a 1000 m radius. Woodlands between 100 and 1000 m of rural houses have intermediate percentages of GSOB damage and unaffected woodlands.

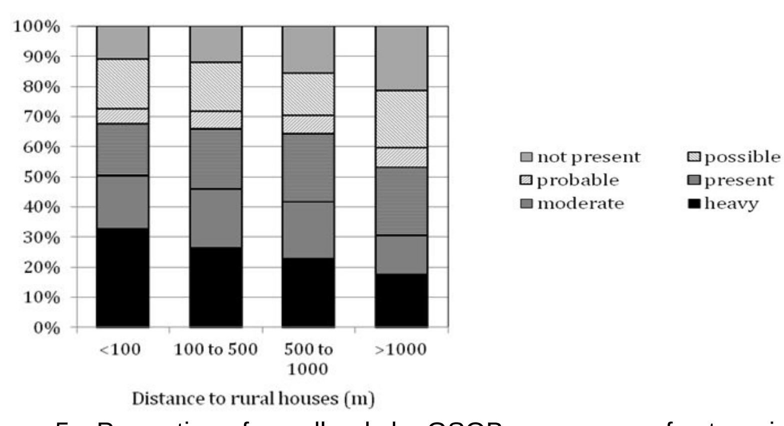

Figure 5—Proportion of woodlands by GSOB occurrence of categories, grouped by distance from rural housing. About half of woodlands within 100 m of rural houses (1650 ha) have heavy to moderate GSOB infestation; only 30 percent of woodlands >1000 m (5750 ha) have this level of infestation. The inverse is true for percentages of uninfested woodlands.

Although we were not able to document oak firewood import by rural homeowners, the intersection of oak woodlands with rural homes appear to be the area where GSOB has had the strongest impact. While it is possible that human activities have led to more GSOB-susceptible trees around rural homes, the most reasonable model is that GSOB was transported to oak trees around these homes and then spread to adjacent woodlands, rather than adult dispersal across the infestation area. This pattern of GSOB dispersal appears similar from the documented spread of the emerald ash borer described by Siegert and others (2014), perhaps at a slightly finer scale of GSOB transport by humans, and presumed dispersal distances by adult beetles.

Origin and rates of GSOB spread

Elevated rates of oak mortality (>2 percent per year) were first visible in the 2002 aerial photo of a plot in Descanso (32.855^o,-116.255^o). This plot had 44 dead oaks in 2002, after having 59 oaks in decline in 1996 (the previous aerial photo). Sixteen plots had substantial numbers of declining oaks (>10) by 2002, but no visible mortality. Eight of these plots had >40 declining oaks in 2002, suggesting that declines began several years earlier. Plots developing abnormal rates of oak mortality peaked in 2006, but continued through 2012. All 75 plots ultimately suffered abnormal rates of mortality, but 12 plots had peak mortality in 2003/2004, where GSOB-impacts could not be separated from damage caused by wildfires in November 2003. The absence of aerial photos between 1996 to 2002 makes it difficult to fully describe the onset of GSOB impacts, but it appears that GSOB-associated oak declines began in the years immediately preceding 2002, and spread to current extent by 2006, 5 to 7 years later. There is no discernable pattern of GSOB spread (fig. 6), except GSOB-impacts first appear near Descanso and stay within about 150 km^2 area for a short time, and then spread by diaspora across the zone of infestation in less than 5 years. This pattern reinforces the importance of transport, with less support for dispersing flights of GSOB adults.

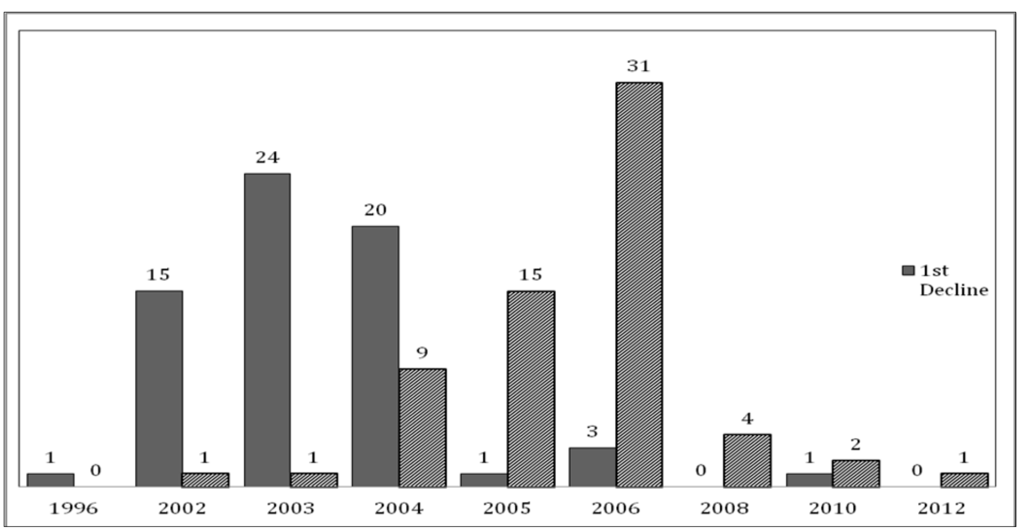

Figure 6—Frequency distributiion of sequential aerial photo plots (n = 65) by first year of decline and first year of mortality. The medium year of first decline was 2003. Medium year of first mortality was 3 years later, 2006.

The number of dead oaks grew from 44 canopies in 2002 to approximately 1000 canopies in 2009 across all plots with evidence of GSOB occurrence (n = 63). This rates of dead oaks/year, however, dropped by almost 50 percent in 2010 (to 546), and dropped again by over 50 percent in 2011 (to 246). Precipitation in the infestation area in 2010 was considered typical after 8 low years, and precipitation in 2011 was considered exceptionally high (SDCWA 2014). In 2012, GSOB-associated oak mortality increased again to 2000 trees, in a year when precipitation dropped far below normal. A similar increase in oak mortality occurred in 2006, also a drought year that followed a year (2005) of abnormally high precipitation. Comparisons of oak mortality across these wet and dry cycles are confounded by (1) the increasing area of GSOB infestation, (2) increasing age of GSOB attacks at individual plots, and (3) the declining numbers of remaining susceptible oaks on plots. Nevertheless, it is difficult to ignore the apparent impact of good years of precipitation on oak survivorship.

GSOB-associated oak canopy death ranged up to 74 percent loss on a plots with >9 years of GSOB damage, compared to a maximum of 3 percent loss in 12 plots without GSOB present. Plots near the center of the infestation area (Descanso, Pine Valley, and Julian) had a median loss of 36 percent of oak canopy area, while plots on the margin of the infestation area had median loss of 18 percent of canopy. On an annual basis, plots with >9 years of GSOB damage lost an average of 326+58 (SE) m^2/ha/year of canopy. This represents an average annual loss of about 3 percent of the canopy, or the equivalent of about four mature oak trees/year on each plot. Rates increased dramatically in the first 3 years of GSOB outbreak; however, the worst mortality was recorded during drought years (2004, 2007, and 2012), with some plots losing up to 25 percent of their oak canopy in a single year. Plots with the longest record of GSOB attack typically had 75 to 100 percent of oaks in some state of decline, basically leaving only the smaller oaks hybrids with interior live oak (*Q. wislizenii*) unaffected.

Individual oaks on sample plots appeared in decline for up to 11 years before dying (declining 2002 to dead 2013). The median numbers of years in decline was 3 (n = 7916); with 70 percent of oaks dead in 4 years, 87 percent dead in 6 years, and 96 percent dead in 8 years. These estimates of oak decline are commensurate with median number of years (3) between first decline and first mortality observed across plots with GSOB.

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