Seasonal Adult Emergence Patterns and Soil Larval Distribution of *Diaprepes abbreviatus* (Coleoptera: Curculionidae) in Southern California[1]

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Abstract Diaprepes root weevil, *Diaprepes abbreviatus* L., was first found in southern California in 2005 and has since spread to citrus groves in a small area of southern California. To develop pest management programs for this pest, its seasonal abundance and distribution of immature stages (including teneral adults) in the soil were investigated. The seasonal abundance of *D. abbreviatus* adults was monitored with modified Tedders traps. Emergence of *D. abbreviatus* adults from soil pupation chambers occurred throughout most of the year, and peak emergence occurred from July to October. However, there was no secondary annual peak emergence over the 4 yr of study in California as has been observed in Florida, suggesting diaprepes root weevil is univoltine in southern California's cooler climate. Annual emergence cycles mirrored patterns of air temperature rather than rainfall. Seasonal abundance and the impact of climate on range expansion of diaprepes root weevil are discussed. The effect of the number and arrangement of traps on the number of adult *D. abbreviatus* caught was also investigated, and we determined that they did not have an effect on adult *D. abbreviatus* trap catch data. Immature life stages in the soil occurred under the tree drip line within the top 30.5 cm of soil and horizontally up to 96.5 cm from the tree trunk. The majority were observed between 17.8 and 45.7 cm from the crown of the trees, which is in the area of Tedders trap placement.

Key Words root weevil, seasonal abundance, invasive pest, citrus, phenology

The diaprepes root weevil, *Diaprepes abbreviatus* L., a polyphagous weevil species native to the Caribbean region (Wolcott 1933, O'Brien and Wibmer 1982), is a serious pest of citrus because of the damage caused by the root-feeding larval stages (Nigg et al. 2004). The weevil was first reported in Florida in 1964 (Woodruff 1968) and has since spread to many of the citrus growing regions of the United States (Martin et al. 2012). In California, diaprepes root weevil was first reported in residential plantings in Newport Beach and Long Beach in 2005 and in San Diego in 2006. In response to these finds, the United States Department of Agriculture Animal and Plant Health Inspection Service and California Department of Food and

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Agriculture (CDFA) formed a technical working group to determine the threat the weevil posed to citrus production in California and to recommend an appropriate course of action. As a result, CDFA established quarantines around weevil-infested sites and began an insecticide treatment program in infested areas of southern California in 2005 and 2006. Due largely to the cost of these treatments, the insecticide treatment program ended in 2008 and research began on integrated pest management programs for this weevil in California.

Understanding the seasonal emergence patterns and life history of the weevil in a newly invaded area is the first step in the development of management programs. Studies of the seasonal emergence patterns had not been conducted in California; however, in Florida the emergence pattern shows a distinct seasonality with a peak in adult emergence in the spring and sometimes a secondary fall peak (Stansly et al. 1977, Duncan et al. 2001, McCoy et al. 2003, Lapointe et al. 2007). Air and soil temperatures play a role in the timing of development and emergence of the diaprepes root weevil (Lapointe 2000, 2001), and it is most abundant in South Florida where winters and summers are warmer than in the central and northern areas (McCoy et al. 2003, Lapointe et al. 2007). The lack of northerly movement in Florida suggests that climate plays a dominant role in determining the geographical range of the diaprepes root weevil (Lapointe et al. 2007).

Monitoring when adult *D. abbreviatus* emerge and where larvae are present in the soil can be determined using modified Tedders traps. The number of weevils found in the traps has been shown to be a reliable indicator of seasonal abundance of adults as well as soil-inhabiting life stages in Florida (Tedders and Wood 1994, McCoy et al. 2003). However, the optimal number and the placement of traps to best monitor diaprepes root weevils in the hilly small acreage production of southern California have not been determined. In addition, the distribution of the immature stages in the soil under the tree canopy has not been determined and should be known to effectively apply pest management practices. In this study, we determined the seasonal emergence patterns of diaprepes root weevil in southern California citrus, investigated the number of Tedders traps needed for effective monitoring of weevil densities, and determined the location of immature stages in the soil relative to the tree trunk.

Materials and Methods

To describe the seasonal emergence patterns of *Diaprepes* in southern California, transects were established in six separate groves of Meyer lemon, *Citrus limon* × *Citrus reticulata* 'Meyer', in quarantine areas of Encinitas, San Diego County. These sites varied little environmentally, with grove area, slope, soil type, and a history of the pesticide treatment applications from 2008 to 2010 for each grove in the transect study listed in Table 1.

The geography of the area used in this study was mostly rolling hills, so the majority of the groves chosen were located on a hillside and were a mix of cardinal-directed slopes. As such, groves are watered by microsprinklers at rates of 56.8 to 64.4 L per hour for approximately 6 h every 2 weeks during the late spring, summer, and early autumn. Irrigation is not typically applied during the winter months when rain events are common.

Table 1. Grove area and slope direction, soil type, and pesticide treatments at the six diaprepes root weevil study sites in Encinitas, San Diego County, CA.

Site	Grove Area in Hectares (Slope Facing Direction)	Insecticide-Miticide Treatments (*n*)		
		2008	2009	2010
1	1.21 (N)*	Lorsban (1) Agri-Mek (1) Omni Oil (1)	Provado (1) Epi-Mek (1) Omni Oil (2)	Lorsban (1) Provado (1) Danitol (1) Sevin (1) Omni Oil (2)
2	0.41 (flat ground)*	Lorsban (2) Baythroid (1) Brigade (1) AE F106464 (1)	Lorsban (3) Agri-Mek (2)	Lorsban (4) Sevin (1)
3	0.688 (ESE)*	Lorsban (3) ABBA (2) AE F106464(1)	Lorsban (4) Sevin (1) Agri-Mek (1)	Lorsban (4) Sevin (1)
4	0.24 (SE)*	Lorsban (1) Agri-Mek (1) Omni Oil (1)	Lorsban (1) Provado (1) Epi-Mek (1) Omni Oil (1)	Lorsban (1) Provado (1) Danitol (1) Sevin (1) Omni Oil (2)
5	0.41 (E)*	Lorsban (1) Agri-Mek (1) Omni Oil (1)	Provado (1) Agri-Mek (1) Omni Oil (2)	No pesticide application
6	0.51 (W)**	No pesticide application	Lorsban (1) Danitol (1) Omni Oil (1)	Lorsban (1) Provado (1) Danitol (1) Omni Oil (2)

* Soil type is Altamont clay.
** Soil type is rocky silt loam.

Pesticides used on the trees in this study were applied by commercial applicators to control other insects and mites, and most are considered effective against *D. abbreviatus* adults (Nigg et al. 2004). Therefore, all sites are considered treated sites. We were unable to obtain a site for our surveys that was organic or untreated. The goals of some of the pesticide applications were to reduce the number of adult *D. abbreviatus*, which in turn would have reduced the number of eggs laid. Further, some of the applications reduced the number of larvae entering the soil, which is considered by many in Florida to be a viable management tactic (Nigg et al. 2004).

To assess seasonal emergence patterns, a single transect of 10 modified Tedders traps was established in each study grove. Each transect ran north to south across the grove and was composed of 10 contiguous trees with one modified Tedders trap located under each tree, approximately 1 m from the tree trunk under the tree canopy. The length of each transect was approximately 36.6 m. Once every 2 weeks, all weevil adults captured in the modified Tedders traps in each transect were collected and recorded. Data were pooled by month for presentation of results.

Rainfall data were provided by the National Oceanic and Atmospheric Administration U.S. Weather Service and collected from the weather station at McClellan-Palomar Airport in Carlsbad, CA. We extracted the total rainfall per month from 2008 to 2011. The airport is located approximately 12.9 km north of the Encinitas study sites, and data from this site are a good representation of the seasonal climatic conditions of coastal southern California.

Air temperatures were collected in close proximity (<5 km) to the transect study sites described below. The data were obtained from Weather Underground (www.wunderground.com) for 2008 through 2011.

To determine the effect of the numbers of traps placed in a grove on capture of adult Diaprepes after emergence from the soil, three groves were selected from among the lemon groves in our transect study which were of a size and shape to allow for selection of an 8×8 block of trees in each grove. The groves chosen were those listed as sites 1, 3, and 5 in Table 1. The trial extended over 3 mo—August, September, and October 2012—because we had previously determined that the peak months for adult *D. abbreviatus* emergence from the soil are July–November in southern California. The number of traps per site was changed each month so that each site was studied with 4, 8, and 16 traps. At the beginning of August, 4 modified Tedders traps were placed in Grove A, 8 traps in Grove B, and 16 traps in Grove C. At the beginning of September, the number of traps in each grove was changed so that Grove A had 8 traps, Grove B had 16 traps, and Grove C had 4 traps. Again, *D. abbreviatus* adults were collected from the traps each week for 4 weeks. At the beginning of October the number of traps in each Grove was changed so that Grove A had 16 traps, Grove B had 4 traps, and Grove C had 8 traps, and data were collected as in August and September. The patterns of trap placement were identical for each of the three groves. *Diaprepes abbreviatus* adults were collected from each trap each week for 4 weeks, and data were pooled by the number of traps placed in a grove.

In 2007, a trial was conducted to determine the abundance and location of the different life stages of diaprepes root weevil in the root zone of trees that were declining due to root damage by *Diaprepes* larvae coupled with entry by *Phytophthora* fungal organisms. The trial was conducted in a lemon grove located on a steeply sloping east-facing hillside with Altamont clay soil. The grove was chosen because it had numerous trees declining and dying. Trees were rated visually from 0 to 5 to indicate the degree of symptoms of decline, with 0 being a healthy tree and 5 being a dead tree. Trees rated as 3 were chosen for the trial. Soil under half of the drip line of each tree (the northern hemisphere), composed of an up-slope quadrant and a down-slope quadrant, was excavated by hand to a depth of 38.1 cm and a distance of 91.4 cm from the tree trunk (approximately to the drip line). The soil was examined in increments of 7.6 cm depth, and the number of weevil life stages was recorded. The life stages in the soil consisted of larvae,

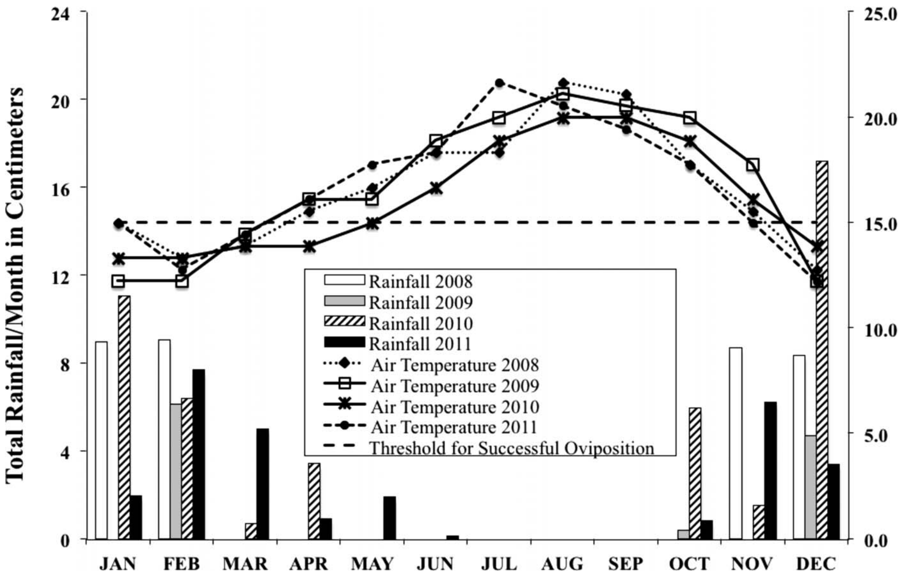

Fig. 1. Total monthly rainfall (cm) (indicated by bars) and average monthly air temperatures (°C) for the area of San Diego, CA where transects were established and where CDFA trap data were collected from 2008 through 2011.

pupae, and teneral adults (collectively referred to as life stages). For each weevil, horizontal distance from the tree trunk and depth were recorded.

Statistical analyses. Data for the horizontal and vertical distribution of *Diaprepes* life stages in the soil and the trap number study were analyzed using analysis of variance (Proc GLM, Statistical Analysis Systems, V9.1). Trap number and study site were considered main effects in the analysis of the trap number study. Data were transformed using log+1 to satisfy the assumptions of the analysis, and means were separated using Fisher's least significant difference ($P = 0.05$).

Results

In the study area, the total monthly rainfall clearly indicated that the rainy season occurred between October and April (Fig. 1), with little or no rainfall between May and September. The average air temperatures peaked during the summer months of July to September (Fig. 1). Air temperatures began to increase in May and continued to increase to a peak between July and August. Beginning in September, mean air temperatures dropped continuously, reaching lows during December and January (Fig 1).

The number of Diaprepes root weevil adults trapped during 2008 to 2011 in the six lemon groves consistently showed peak emergence during the warmer months

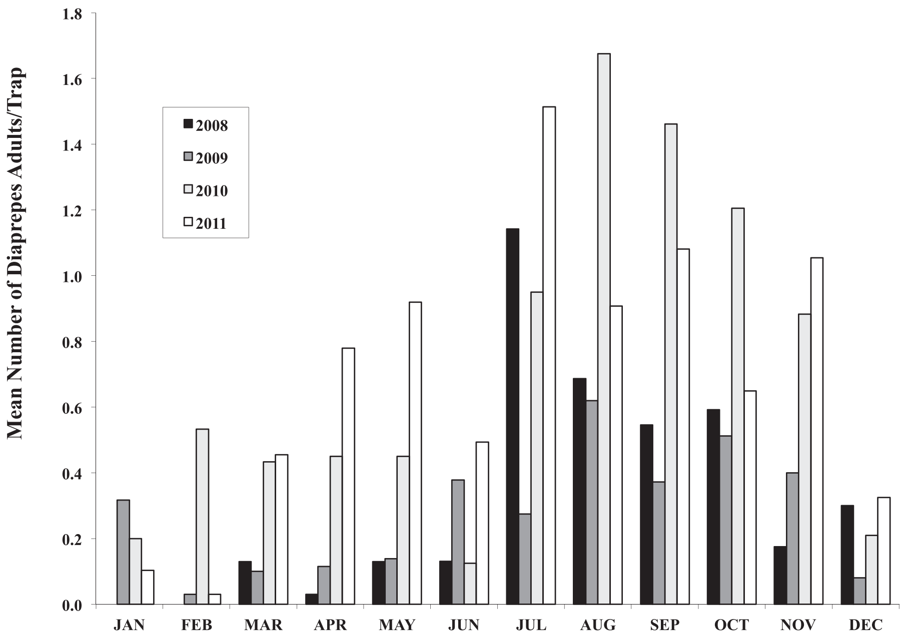

Fig. 2. Mean number of Diaprepes root weevils collected from modified Tedders trap from 2008 to 2011 in six lemon groves in San Diego County, CA.

of July to October (Fig. 2). In 2010, southern California experienced a lengthy, cooler spring that delayed peak emergence until August. Greater numbers of adults were captured during August to November in 2010 compared with any other annual cycle. The largest numbers of adults in 2011 were trapped from April to July. The larger trap catches in both 2010 and 2011 were associated with air temperatures observed during those sampling months (Figs. 1, 2) and with the cessation of pesticide applications by the CDFA for eradication efforts.

Trap catches for each of the trap densities used in the density study can be found in Table 2. There were no significant differences in trap catches among locations ($F = 0.16$; df = 2,4; $P = 0.8502$) or significant interaction ($F = 1.81$; df = 4,75; $P = 0.1354$) between number of traps and location. However, the total numbers of adult *D. abbreviatus* trapped at each study site were statistically different ($F = 27.01$; df = 2,4; $P < 0.0001$; Table 2).

Although there was a trend toward fewer life stages collected at the lowest depth of 25.4–30.8 cm below the trees, there was no significant difference ($F = 0.9$; df = 3,21; $P = 0.4596$) in the mean number of larvae captured at the three sampled depths (Table 3). There was a significant difference ($F = 10.42$; df = 5,35; $P < 0.0001$), however, in the mean number of life stages collected at selected horizontal distances from the crown of the trees. The majority of the larvae tended to be feeding at between 17.8 and 45.7 cm from the crown of the trees (Table 4).

Table 2. Mean number (±SE) of diaprepes root weevil (DRW) adults collected from modified Tedders traps in three small lemon groves in San Diego County, CA. In each grove, traps were placed at densities of 4, 8, and 16 per 0.4 ha. Patterns of trap placement were identical for each grove.

Trap Density/0.4 ha	Mean No. DRW Adults/Trap
4	2.8 ± 1.6a
8	2.0 ± 0.5a
16	2.6 ± 0.6a

Means followed by the same letter are not significantly different, Fisher's Least Significant Difference ($P = 0.05$).

Discussion

In this study, we monitored the seasonal emergence patterns of adult *D. abbreviatus* from 2008 to 2011 using modified Tedders traps in six citrus groves in Encinitas, CA, USA. We also investigated the number and arrangement of traps within three small citrus groves and found that there was no difference in the number of adult weevils trapped when using 4, 8, or 16 traps in an 8 × 8 block of citrus trees. Finally, we determined the distribution of weevil grubs in the soil around the citrus tree roots and found that there was no difference in the number of larvae found at any particular depth. We did find, however, that there were statistically more larvae found closer to the main trunk of the tree compared to farther out from the tree.

In general, emergence of adults in our study area increased during the warmer 6 mo of the year, May to October, and was minimal during the cooler 6 mo of the year, November to April. *Diaprepes abbreviatus* adults emerged year-round in southern California but had a single peak in emergence during the summer months. Our data suggest that rainfall has no influence on seasonal emergence peaks in southern California, where rains end in early spring and peak emergence is in mid-summer.

Table 3. Mean number (±SE) of diaprepes root weevil immature stages (including teneral adults) collected at the depths indicated from soil below lemon trees in a small orchard in San Diego County, CA.

Depth (cm)	Mean No. /Tree
0–7.6	5.0 ± 1.9a
10.2–15.2	6.0 ± 2.2a
17.8–22.9	5.6 ± 1.5a

Means followed by the same letter are not significantly different, Fisher's Least Significant Difference ($p = 0.05$).

Table 4. Mean number (±SE) of diaprepes root weevil immature stages (including teneral adults) collected from soil at different distances from the trunk of lemon trees in a small orchard in San Diego County, CA.

Horizontal Distance (cm) from Tree Trunk	Mean No. of Immatures/ Tree
0–15.2	1.7 ± 0.1bc
17.8–30.5	6.1 ± 1.7a
33.0–45.7	6.4 ± 2.0a
48.3–61.0	2.9 ± 1.1b
63.5–81.3	2.0 ± 0.5b
83.8–96.5	0.2 ± 0.2c

Means followed by the same letter are not significantly different, Fisher's Least Significant Difference ($P = 0.05$).

Patterns of emergence in Florida can vary considerably (McCoy et al. 2003, Nigg et al. 2004), but two emergence peaks are common. A similar variable emergence pattern has been observed in California, where low emergence numbers have been observed throughout most of the year and peak emergence occurs from July to October, suggesting seasonality. However, we did not observe a secondary peak emergence over the 4 yr of study in California, suggesting diaprepes root weevil might be univoltine in southern California's cooler climate.

LaPointe and Shapiro (1999) and McCoy et al. (2003) noted that the onset and magnitude of adult emergence might be delayed by soil moisture deficit. Soil moisture deficit is pronounced in the typical dry southern California summer, especially near the soil surface. Therefore, a delay of the first emergence of diaprepes root weevils in California in early summer before regular irrigation commences is likely, increasing the amplitude of adult emergence just prior to the return of cooler temperatures, hence causing a single annual emergence peak.

The single annual emergence peak may be one explanation of why the diaprepes root weevil has not expanded its range as rapidly as expected in southern California. Lapointe et al. (2007) concluded that the lack of northerly dispersal into Florida above the 28th degree of latitude, in spite of the presence of suitable hosts, suggested that climate plays a dominant role in determining diaprepes root weevil geographic range. However, *Diaprepes* survives well in the cooler oceanic climate of coastal California (Florida State University 2012, Western Regional Climate Center 2012), which is above the 32nd degree of latitude. Further, oceanic conditions are similar along the California coast northward to San Francisco, which suggests that *Diaprepes* may possibly establish in areas north of Los Angeles County along the coast. Lapointe et al. (2007) used a climate homology model to map the potential distribution of *Diaprepes* in California and suggested that portions of San Diego County and coastal areas of Orange, Los Angeles, Ventura, and Santa Barbara counties have the most potential for *Diaprepes* establishment. The model corresponds nicely with the current find sites in Los Angeles, Orange, and San Diego counties, but *Diaprepes* has not yet been found north of Los Angeles in Ventura and Santa Barbara counties.

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