

Life History of *Parthenolecanium* spp. (Hemiptera: Coccidae) in Urban Landscapes of the Southeastern United States

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Abstract

This study was conducted to better understand the life history of *Parthenolecanium corni* (Bouché) and *Parthenolecanium quercifex* (Fitch) (Hemiptera: Coccidae), and to develop degree-day models for crawler emergence of the two soft scale species in Georgia, North Carolina, South Carolina, and Virginia. Both species were univoltine in the southeastern United States. In South Carolina, eggs hatched from mid-April to early June; second instars began to appear in September and migrated to twigs to overwinter in October; and third instars and adults appeared in mid-March to early April. Each parthenogenetic female produced on average $1,026 \pm 52$ eggs. Fecundity was positively correlated to the fresh weight, length, width, and height of gravid females. Gross reproductive rate (GRR) was 695.98 ± 79.34 ♀/♀, net reproductive rate (R_0) was 126.36 ± 19.03 ♀/♀, mean generation time (TG) was 52.61 ± 0.05 wk, intrinsic rate of increase (r_m) was 0.04 ♀/♀/wk, and finite rate of increase (λ) was 1.04 times per week. Crawlers first occurred across Georgia, North Carolina, South Carolina, and Virginia in 2011–2013 when 524–596 Celsius-degree-days (DDC) had been accumulated with the single sine estimation method, or 411–479 DDC with the simple average method, at the base temperature of 12.8°C and the start date of 1 January. These regional models accurately predicted the date of crawler emergence within 1 wk of the actual emergence in 2014.

Key words: degree-day model, soft scale, shade tree, pest management

Parthenolecanium (Hemiptera: Sternorrhyncha: Coccidae) is a cosmopolitan genus that feeds mainly on trees and shrubs (Kozár and Ben-Dov 1997). Of the six species in the United States (García Morales et al. 2016), four are common pests of ornamental plants in the eastern region: European fruit lecanium, *Parthenolecanium corni* (Bouché); Fletcher scale, *Parthenolecanium fletcheri* (Cockerell); European peach scale, *Parthenolecanium persicae* (F.); and oak lecanium, *Parthenolecanium quercifex* (Fitch).

In urban landscapes of the southern United States, *P. corni* and *P. quercifex* are pests of woody ornamental plants, such as hickory (*Carya* spp.), maple (*Acer* spp.), persimmon (*Diospyros* spp.), sycamore (*Platanus occidentalis* L.), and wax myrtle (*Myrica cerifera* L.) (Sanders 1909, Williams and Kosztarab 1972, Hodges and Braman 2004). They are most commonly found on oaks (*Quercus* spp.), where a large population produces copious honeydew and can

reduce tree vigor and growth (Schultz 1984, 1985; Meineke et al. 2016). Despite their pest status, phenology and life history of *P. corni* and *P. quercifex* in the southeastern United States are not well known. *Parthenolecanium corni* and *P. quercifex* have been reported to be univoltine in Virginia (Williams and Kosztarab 1972, Day 2008) and California (Kawecki 1958, Madsen and Barnes 1959, Swiecki and Bernhardt 2006). Hodges and Braman (2004) reported the occurrence of one complete and a second partial generation of *P. corni* in Georgia. Meineke et al. (2014) reported phenology of *P. quercifex* egg production on urban trees. No additional phenological studies have been reported for *P. quercifex*.

Careful timing of control measures, informed by pest phenology, is critical to the management of landscape pests (Ascerno 1991, Raupp et al. 1992, Mussey and Potter 1997, Robayo Camacho and Chong 2015). The crawlers and settled first instars of soft scale

insects in the subfamily Coccinae is the only life stage without the protection of a waxy cover or deposit (Hodges and Braman 2004, Robayo Camacho and Chong 2015). Consequently, it is the life stage most vulnerable to contact insecticide applications. However, tools that predict the timing of crawler emergence have limited availability and are underutilized by pest and plant management professionals (Raupp 1985). Poor understanding of the biology and life cycle of *P. corni* and *P. quercifex* hinders the development of a well-timed and effective management program.

Insect life history events can be predicted by phenological models based on degree-day (DD) accumulations (Mussey and Potter 1997, Roltsch et al. 1999). Phenological models are the keys for timing management activities against insect pests (Herms 2004). Degree-day models have been developed for several insect pests of woody ornamental plants, including scale insects (Mussey and Potter 1997, Herms 2004, Hodges and Braman 2004).

Hodges and Braman (2004) developed a degree-day model to predict crawler emergence of *P. corni* in Athens, GA, based on degree-day accumulation using an experimentally derived temperature of 12.78 °C (55 °F) and single-sine method. They found means of 1203, 1198, 1263, and 1209 Celsius-degree-days (DD) for first crawler emergence in 1997, 1998, 1999, and 2000, respectively. Degree-day models for crawler emergence of *Parthenolecanium* spp. are not available for other southeastern states, and it is not known if a regional model can accurately predict the crawler emergence in the entire southeastern United States.

Knowledge of basic pest biology is needed to better understand the complex interactions between plants and their herbivorous insect associates, which consequently allows for wise decision-making concerning pest management. The goal of our research is to provide pest managers with phenological and biological information to inform management decisions against *Parthenolecanium* spp. in the urban landscapes of the southeastern United States. This study had the following objectives: 1) to document the phenology, fecundity, and survivorship of *Parthenolecanium* spp.; 2) to determine the correlation between fecundity and adult female body size; 3) to estimate life table parameters (gross reproductive rate, net reproductive rate, mean generation time, intrinsic rate of increase, and finite rate of increase); and 4) to develop state and regional degree-day models that accurately predict crawler emergence of *Parthenolecanium* spp.

Materials and Methods

Life History of *Parthenolecanium* spp.

We sampled for the abundance and life stage of the *Parthenolecanium* spp. populations on six willow oak (*Quercus phellos* L.) trees at the Pee Dee Research and Education Center in Florence, SC. The trees were planted in narrow islands of turfgrass surrounded by a paved parking lot. The trees were about 7–9 m tall, 0.1–0.3 m in diameter at breast height, and 5–6 m in canopy width. The trees were infested with a mixed population of *P. corni* (20%) and *P. quercifex* (80%). It is difficult to distinguish between adult females of *P. corni* and *P. quercifex*. Identification of the two species can only be achieved by examining crawlers under compound microscopes at high magnification (Hodges and Williams 2003). *Parthenolecanium corni* and *P. quercifex* are often regarded by landscape and extension service professionals generally as the “lecanium scales” because of their similarities in morphology and biology (Baker 1994, Townsend 2005). Therefore, the two species were treated in this study as a group, *Parthenolecanium* spp. The scale insect population was not treated with insecticides during the study.

One twig (10–15 cm) was collected from each of the four cardinal directions of each tree, weekly in March to November and bi-weekly in December to February 2009–2013. Scale insects feeding on five leaves (selected randomly from each twig) and the twig were counted under microscopes. The average density (number of individuals per leaf or per cm of twig) of each developmental stadium was plotted against time to identify seasonal changes in density.

Fecundity of females was determined by collecting and dissecting 18 haphazardly collected gravid females (three females per tree) near the end of reproductive period in early to mid-May 2013. Each female (with its full complement of eggs) was weighed before the eggs were counted under microscopes. Measurements of the physical characteristics of the female tests (height—the greatest distance from the venter to the dorsum, perpendicular to the venter; length—the greatest distance from the distal margin of the anterior end of head to the distal margin of the posterior end of the abdomen, parallel to the mid dorsal line; and width—the widest distance between the two sides, perpendicular to the mid-dorsal line) were taken with the software ProgRes CapturePro v2.8.8 (I-Solution, Image and Microscope Technology Inc., Vancouver, BC, Canada). The relations between the fecundity and the physical characteristics of the test, and the combined weight of the females and egg mass, were determined through Pearson correlation and linear regression (PROG CORR and PROG REG; SAS Institute Inc 2011). Parasitized scales were excluded from the assessment.

A life table of *Parthenolecanium* spp. was developed based on 1) the number of surviving individuals at each sampling date in the life history study, and 2) the age-related fecundity (of adult females) from the fecundity study. The survival rate (l_x) is the probability that a first instar to survive until a specific sampling week (x); the age-related fecundity (m_x) is the average of eggs produced by each adult female at week x (Birch 1948). The survival rate was estimated based on the average total numbers of live individuals at each life stage in each week between April 2012 and June 2013 (one generation), expressed as a fraction of an initial population of crawlers (Southwood and Henderson 2000). After plotting the graph based on the number of eggs produced by a female during the entire ovipositing season, the fecundity per week was calculated by relating the corresponding area under the graph to the total number of eggs produced (i.e., the peak of the graph).

The following life table parameters were estimated for each cohort from each tree: gross reproductive rate, $GRR = \sum m_x$; net reproductive rate, $R_0 = \sum (l_x m_x)$; mean generation time, $T_G = \sum (x l_x m_x) / \sum (l_x m_x)$; intrinsic rate of increase, $r_m = (\ln R_0) / T_G$; and finite rate of increase, $\lambda = \exp(r_m)$ (Birch 1948).

Degree-Day Predictive Models for Crawler Emergence

Willow oak trees infested with *Parthenolecanium* spp. in Griffin, GA (two trees); Raleigh, NC (five trees); Florence, SC (six trees); and Virginia Beach, VA (two trees), were monitored weekly from March to June 2011–2013. The dates of first crawler emergence were recorded at each site. Mixed populations of *P. corni*–*P. quercifex* were found in all states: Georgia, 50–50%; North Carolina, 60–40%; South Carolina, 20–80%; and Virginia, 30–70%.

Centigrade degree-days accumulation (in DD) was estimated in each year (2011–2013) for each site from 1 January to the observed date of first crawler emergence using ambient temperature data collected by nearby weather stations (AB4KN Fayetteville, GA [15 km to the test site in Griffin]; CW2094 Raleigh, NC [10 km to the test site in Raleigh]; AS045 KD4VH Quinby, SC [8 km to the test site in Florence]; CW7042 Norfolk, VA [15 km to the test site in Virginia

Beach]) (OSU 2016). State-specific degree-day models were developed using unique combinations of each of the three common estimation methods (single-average, single-sine, and single-triangle) and each of the five base temperatures (1.6°C [35°F], 4.4°C [40°F], 7.2°C [45°F], 10°C [50°F], and 12.8°C [55°F]). These base temperatures have been used in developing degree-day models for insect pests in urban landscapes (Mussey and Potter 1997), or experimentally established at 12.8°C for *P. corni* (Hodges and Braman 2004). The predicted crawler emergence dates and DDC of the 3-yr models were compared against actual dates and the corresponding DD accumulation in 2014 to determine the accuracy of the model.

State models for Georgia, South Carolina, and Virginia, and a regional model, were developed sequentially by selecting models with the least differences in predicted and actual crawler emergence dates or DDC. First, all degree-day models developed with the same estimation method for each state were examined (regardless of the base temperatures), and those which produced the least differences in predicted and actual emergence dates and DDC were selected. At the end of this step, the selected models included those developed at each state with each of the estimation method. In the next step, the models with the least differences in predicted and actual DDC (regardless of the estimation method) were selected for each state (these are the state models). The state models were examined, and the state models with repeated estimation method and base temperature were selected for consideration as the regional model. Finally, one model (from among the selected state models) with the least differences in predicted and actual DDC was selected as the regional model. The regional model was presented as a range of the average low DDC and average high DDC across all three years and all three states.

Results and Discussion

Phenology and Life History

In this study we found *P. corni* and *P. quercifex* to be univoltine in the southeastern United States. The two species were reportedly univoltine in California (Kawecki 1958, Madsen and Barnes 1959, Swiecki and Bernhardt 2006) and Virginia (Williams and Kosztarab 1972, Day 2008). However, there could be variations in voltinism of *P. corni*. *Parthenolecanium corni* has been reported to have two generations in Chile (Bayer CropScience Chile 2014), Hungary (Kosztarab 1959), and Russia (Borchsenius 1957). Hodges and Braman (2004) reported one generation of *P. corni* in 1997 and 2000, and two generations in 1998 and 1999 in Georgia with the second-generation crawlers hatching in early autumn. In our study a mixed population of *P. corni* and *P. quercifex* had only one generation per year across Georgia, North Carolina, South Carolina, and Virginia.

Eggs hatched between mid-April to early June in South Carolina (Fig. 1). After eclosion, the crawlers dispersed to, settled, and fed on nearby leaves. First instars of *P. quercifex* (Williams and Kosztarab 1972) and *P. corni* (Kosztarab 1996) have been reported to settle on the underside of leaves. Hubbard and Potter (2005) reported finding crawlers of calico scale, *Eulecanium cerasorum* (Cockerell) (Hemiptera: Coccidae), settling mostly on the underside of leaves, with some variations among host plant species: 99 to 93% of crawlers settled on the underside of honeylocust (*Gleditsia triacanthos* L.) and sweetgum (*Liquidambar styraciflua* L.) leaves, whereas 85% of crawlers settled on the underside of hackberry (*Celtis occidentalis* L.) and Norway maple (*Acer platanoides* L.) leaves. We observed and collected first instars on both sides of willow oak leaves, but we did not assess the differences between the two sides in the

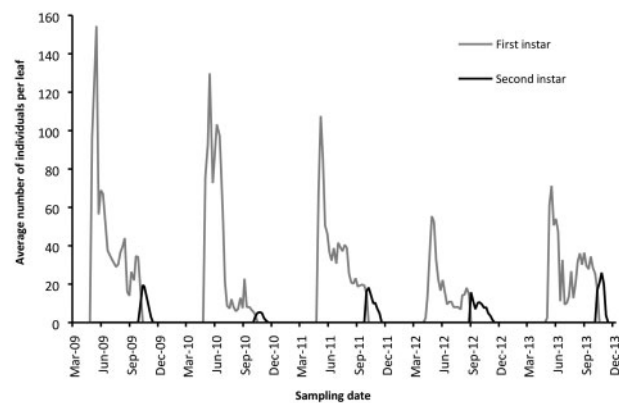


Fig. 1. Average weekly abundance of *Parthenolecanium* spp. life stages on willow oak leaves in South Carolina from 2009 to 2013.

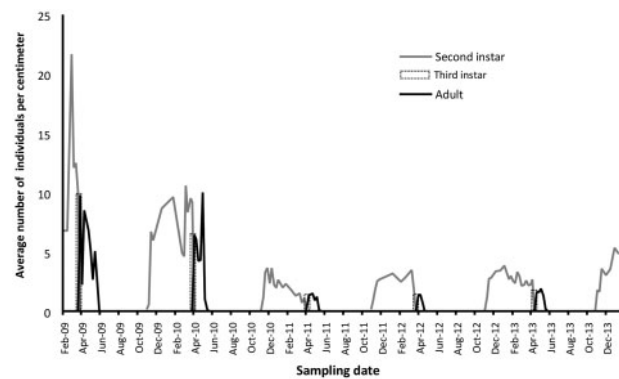


Fig. 2. Average density of *Parthenolecanium* spp. life stages on willow oak twigs in South Carolina from 2009 to 2013.

numbers of settled crawlers. Spraying the underside of leaves with nonresidual contact insecticides is a common recommendation for controlling scale insect infestations (Kabashima and Dreistadt 2014). Further studies exploring differential preference for crawlers of *Parthenolecanium* spp. to settle on either side of the leaves of various host plant species may need to be developed to provide insights on the application method and target of contact insecticides.

First instars are oval and elongated, dorso-ventrally flat, pale brown to yellow, 0.3–0.5 mm in length. Some first instars became almost transparent after settling on their feeding site until the next molt. Timing of the peak density for first instar varied from year to year. The highest densities of first instars were reached on 29 May 2009 (averaged 155 individuals per leaf), 24 May 2010 (130), 16 May 2011 (108), 7 May 2012 (55), and 27 May 2013 (71; Fig. 1).

First instars molted into second instars from mid-September to late-October. The highest densities of second instars were observed on 19 October 2009 (averaged 20 individuals per leaf), 25 October 2010 (5), 17 October 2011 (18), 10 September 2012 (16), and 4 November 2013 (26; Fig. 1). Just before leaf senescence in November, they migrated to the twigs to overwinter. This observation agrees with Marotta and Tranfaglia (1997) generalization that the second instar is the overwintering stage of Nearctic coccids. The highest densities of second instars on twigs in each generation were reached on 23 February 2009 (averaged 22 individuals per cm of twig), 15 March 2010 (11), 13 December 2010 (4), 13 February 2012 (3), and 2 January 2013 (4; Fig. 2).

Second instars have a general appearance similar to that of the first instars, except for their increased size (0.6–0.9 mm in length). The anal plates and the anal cleft are close to the rear end of the body in the first instar, whereas the anal plates seem to have “migrated” anteriorly to about 4/5 of the body in the second instar, almost double the length of the anal cleft. In the first and second instars, the median apical seta of each anal plate is at least half of the body length (Williams and Hodges 1997), but this characteristic is absent in the third instar and adults.

As the leaf buds of the host trees started to break in mid-March to early April, the surviving second instars molted into the third instars (Fig. 2). The third instar lasted about 4 d, after which they eclosed into adults. The short duration of the third instar and its close resemblance to the adult (differentiated by an increase in size, and the appearance of genital aperture and modified integumentary secretory system in adults; Marotta 1997), made the third instar difficult to notice. In this study, we did not observe males in the populations in South Carolina.

Adults increased greatly in size between adult eclosion and initiation of reproduction, and produced copious amounts of honeydew. Adult densities ranged between 1 and 10 individuals per centimeter of twig, and they remained on the twigs until the end of their life (about 4–5 wk). The females began to produce eggs in their brood chambers 5–7 d after adult eclosion. The eggs hatched within 20–25 d. In Virginia, the female of *P. quercifex* has been reported to begin oviposition in early May and egg hatching in late May (Williams and Kosztarab 1972). In North Carolina egg production can begin in mid-March and peak in mid-April (Meineke et al. 2013, 2014). The maturation period of eggs of *Parthenolecanium* spp. seemed similar to that on *S. oleae* and *Ceroplastes rusci* (L.), where hatching occurred within 2–3 wk and 3–4 wk after deposition, respectively (Alford 2012).

Fecundity

A large-scale insect population can cause decline and death of its host plants (Washburn and Washburn 1984). Knowledge on scale insect fecundity and survivorship can help with predicting the population growth rate (through life table analysis) and developing appropriate management plans that could be fine-tuned based on the biology of pest species. Female *Parthenolecanium* spp. in South Carolina deposited 177 to 2,398 (average = $1,026 \pm 52$) eggs over 3 wk in this study. The fecundity of *Parthenolecanium* spp. in South Carolina falls within the range of previously reported fecundity of *P. corni*, which varies from 100 to 5,000 eggs (Fenton 1917, Kaweki 1958, Bailey 1964, Santas 1985, Babaian 1986), and *P. quercifex* (Meineke et al. 2014).

Fecundity and body size are positively correlated in *Ceroplastes destructor* (Newstead) and *Ceroplastes sinensis* Del Guercio (Lo 1995). We determined that the fecundity of *Parthenolecanium* spp. correlated significantly to female body size ($P < 0.01$), supporting similar observation by Marotta (1997). The Pearson correlation coefficient was the highest (0.91) between the weight of the females (including the eggs) and fecundity, followed by length (0.75), width (0.67), and height (0.39). Linear regression analysis corroborated the results of Pearson correlation analysis (Fig. 3). Our results suggested that all the body size parameters were sufficient in predicting the fecundity, but the weight was more accurate than the three size parameters. When gravid female weight is not available, researchers and pest managers can still predict scale insect fecundity with length. Birjandi (1981) demonstrated positive correlation between the volume of *P. corni* and its fecundity [Pearson correlation

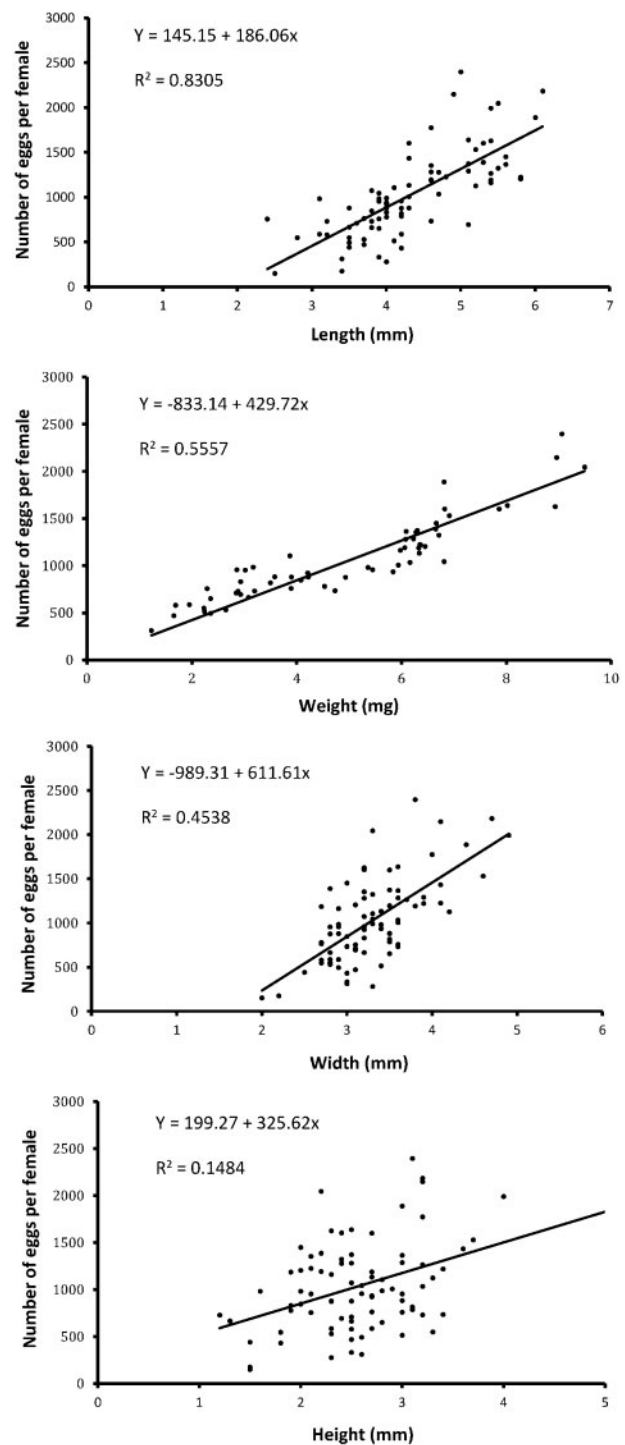


Fig. 3. Relationship between the fecundity and the weight of the female (with eggs), and length, width, and height of the adult female of the lecanium scales.

coefficient = 0.86; fecundity = $236.66 + 35.23(\text{volume})$]. Our results suggest that instead of using volume, measuring weight, or length, using the linear regression equations developed in this study may be an adequate and simpler method in estimating the fecundity of *Parthenolecanium* spp. for a pest management program or an ecological and biological study. This would save researchers time and effort in measuring all body size parameters or counting all the eggs produced by multiple females.

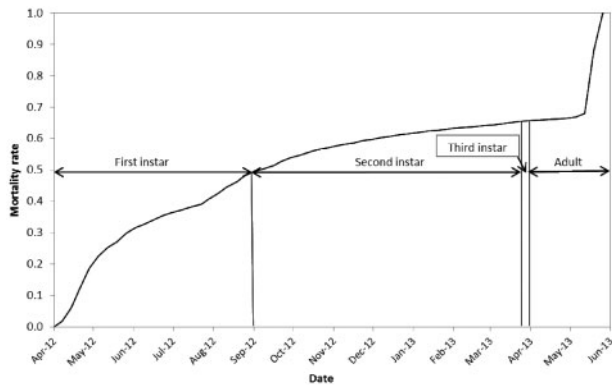


Fig. 4. Mortality rates in one generation (April 2012–June 2013) of *Parthenolecanium* spp. on willow oak in South Carolina.

Survivorship

Accumulated mortality of the first instars approached 50% of the population in one generation, which was higher than the mortality of other life stages (32.7% of second instars and 1.6% of third instars; Fig. 4). The equivalent cumulative survivorship for all stages (Fig. 5) could be also calculated as the accumulated mortality rate subtracted from the total population ($1 - \text{mortality rate}$), from eggs to adults. High mortality during the first instar is a common occurrence in soft scales (Santas 1985, Rainato and Pellizzari 2009), owing to failure in finding an appropriate feeding site (Podoler et al. 1979, Washburn and Washburn 1984), predation (Birjandi 1981), and vulnerability to high temperature, low humidity, heavy rain, and wind (Marotta 1997).

Life Table Parameters

The gross reproductive rate (GRR) was estimated at 695.98 ± 79.34 ♀/♀; net reproductive rate (R_0) at 126.36 ± 19.03 ♀/♀; mean generation time (T_G) at 52.61 ± 0.05 wk; intrinsic rate of increase (r_m) at 0.04 ♀/♀/wk; and finite rate of increase (λ) at 1.04 times per week. R_0 over 1 or r_m over 0 would indicate a population that is increasing, whereas R_0 below 1 or r_m below 0 would indicate a population that is decreasing (Bellows et al. 1992). The R_0 values of *Parthenolecanium* spp. in this study indicate an increasing population. Our r_m value indicates a population that was increasing at a slow pace. With $r_m = 0.04$ ♀/♀/d and $\lambda = 1.04$ times per day, a population of *Saissetia coffeae* (Walker) (Hemiptera: Coccidae) developed rapidly at 18°C (Abd-Rabou et al. 2009) and were greater than those of *Parthenolecanium* spp. in this study.

Our life table parameters for *Parthenolecanium* spp., besides indicating a population that is thriving in South Carolina, can be used in future studies as reference to understand the population dynamics of either the same species covered herein in other locations and conditions, or for comparison with other soft scale species with similar biology. Life table parameters of the *Parthenolecanium* spp. may also be used to better understand the impact of natural enemies on the pest population (Bellows et al. 1992).

We recognize that the life history parameters and population growth models estimated at one site may not predict those same parameters at every location. Beyond differences at large geographic scales, *Parthenolecanium* phenology, reproduction, and survival can differ between nearby trees. For example, trees that are just 2°C warmer can have many times more *Parthenolecanium* scales due to greater survival of first instars (Meineke et al. 2013). The same 2°C of warming also leads greater fecundity because scales develop earlier

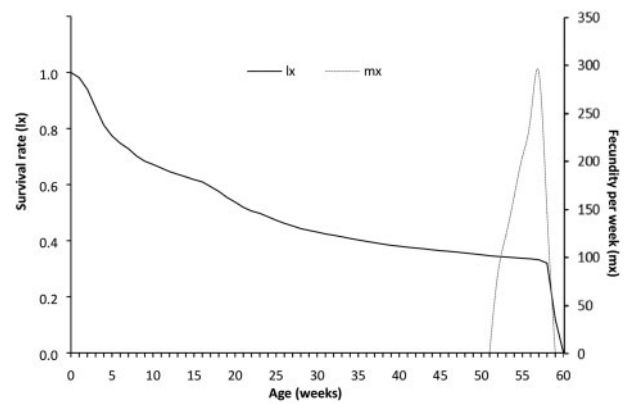


Fig. 5. Survival rates and weekly fecundity in one generation (April 2012–June 2013) of *Parthenolecanium* spp. on willow oak in South Carolina.

Table 1. Week of the year of first crawler emergence from 2011 to 2014 in Georgia (GA), North Carolina (NC), South Carolina (SC), and Virginia (VA)

| State | 2011 | 2012 | 2013 | 2014 |
|-------|---------|---------|---------|---------|
| GA | Week 17 | Week 15 | Week 18 | Week 19 |
| NC | Week 19 | Week 18 | — | — |
| SC | Week 19 | Week 16 | Week 19 | Week 19 |
| VA | Week 20 | Week 17 | Week 19 | Week 20 |

and avoid parasitism (Meineke et al. 2014). Because site characteristics affect the phenology, fitness, and abundance of *Parthenolecanium* and other scales, IPM resources could be focused on the trees that are most vulnerable due to temperature, impervious surface cover, drought, or other stressors (Dale and Frank 2014a, b; Dale et al. 2016).

Degree-Day Predictive Models

The calendar dates for first crawler emergence in 2011 to 2014 ranged from 12 April to 7 May in Georgia, 30 April to 11 May in North Carolina, 17 April to 11 May in South Carolina, and 27 April to 18 May in Virginia (Table 1). Hodges and Braman (2004) reported emergence of *P. corni* crawlers in 23 May to 15 June in 1997–2000 in Georgia. Their results were more than one month later than the emergence dates obtained from the same state in this study. Interestingly, Schultz (1984) also reported crawler emergence times of *P. quercifex* that were over a month later than those dates reported in this study. Warming is a likely mechanism for these differences although we cannot draw firm conclusions, as only a small number of similar studies have been conducted intermittently or continuously over the past three decades. The phenology of many ectothermic species has become earlier owing to climate change in recent decades including many pests (Parmesan and Yohe 2003). The urban heat island effect adds growing degree days and can thus cause insects to develop or become active earlier than in rural areas (Meineke et al. 2014, Schatz and Kucharik 2016). Future climate-induced changes in pest biology will require vigilance by IPM practitioners to maintain accurate pest forecasting tools.

We developed degree-day models for first crawler emergence in Georgia, South Carolina, and Virginia (Table 2). The first step was to identify models with the least difference in predicted and actual DDC of first crawler emergence for each estimation method. The base temperatures with the least differences in predicted and actual DDC and dates with each estimation method for crawler

Table 2. Degree-day accumulation for actual week of first crawler emergence (2011–2013) of *Parthenolecanium* spp. and their differences with predicted dates (2014) using three estimation methods and five base temperatures in three southeastern states

| State | Estimation method | Base temp (°C) | DD accumulation | | | | DD difference range (predicted – actual) | | Predicted wk(s) 2014 | Week difference (predicted – actual) |
|----------------|-------------------|----------------|-----------------|-----------|-----------|-----------|--|------|----------------------|--------------------------------------|
| | | | 2011 | 2012 | 2013 | Avg | Low | High | | |
| | | | | | | | | | | |
| Georgia | Simple average | 1.6 | 2031–2236 | 2050–2195 | 1538–1715 | 1873–2049 | 98 | 138 | 18, 19 | –1, 0 |
| | | 4.4 | 1523–1698 | 1585–1699 | 1113–1260 | 1407–1552 | 33 | 74 | 18, 19 | –1, 0 |
| | | 7.2 | 1089–1234 | 1142–1226 | 741–858 | 991–1106 | –7 | 34 | 19 | 0 |
| | | 10.0 | 718–835 | 759–813 | 452–539 | 643–729 | –25 | 14 | 19 | 0 |
| | Single sine | 12.8 | 412–498 | 459–487 | 252–308 | 374–431 | –41 | –2 | 19, 20 | 0, 1 |
| | | 1.6 | 2074–2280 | 2079–2223 | 1568–1745 | 1907–2083 | 123 | 163 | 18, 19 | –1, 0 |
| | | 4.4 | 1604–1780 | 1637–1751 | 1183–1330 | 1475–1620 | 66 | 106 | 18, 19 | –1, 0 |
| | | 7.2 | 1185–1331 | 1230–1316 | 846–962 | 1087–1203 | 29 | 69 | 18, 19 | –1, 0 |
| | Single triangle | 10.0 | 834–950 | 869–932 | 572–659 | 758–847 | 5 | 42 | 19 | 0 |
| | | 12.8 | 552–640 | 569–613 | 359–416 | 493–556 | –7 | 26 | 19 | 0 |
| | | 1.6 | 2058–2264 | 2069–2213 | 1556–1732 | 1894–2070 | 115 | 155 | 18, 19 | –1, 0 |
| | | 4.4 | 1578–1754 | 1618–1732 | 1159–1306 | 1452–1597 | 55 | 95 | 18, 19 | –1, 0 |
| | | 7.2 | 1153–1299 | 1202–1288 | 813–929 | 1056–1172 | 18 | 57 | 19 | 0 |
| | | 10.0 | 795–910 | 835–895 | 535–622 | 722–809 | –6 | 32 | 19 | 0 |
| | | 12.8 | 509–596 | 534–572 | 324–381 | 456–516 | –20 | 15 | 19 | 0 |
| | | 1.6 | 2433–2661 | 2189–2392 | 2210–2405 | 2277–2486 | –206 | –166 | 19, 20 | 0, 1 |
| South Carolina | Simple average | 4.4 | 1861–2059 | 1681–1855 | 1609–1775 | 1717–1896 | –183 | –143 | 19, 20 | 0, 1 |
| | | 7.2 | 1357–1525 | 1214–1357 | 1105–1241 | 1225–1374 | –155 | –115 | 19, 20 | 0, 1 |
| | | 10.0 | 933–1071 | 813–926 | 725–831 | 824–943 | –111 | –71 | 19, 20 | 0, 1 |
| | | 12.8 | 595–702 | 506–589 | 424–499 | 508–597 | –81 | –41 | 19, 20 | 0, 1 |
| | Single sine | 1.6 | 2492–2719 | 2228–2431 | 2252–2448 | 2324–2533 | –202 | –162 | 19, 20 | 0, 1 |
| | | 4.4 | 1958–2255 | 1762–1935 | 1711–1877 | 1810–2022 | –184 | –178 | 19, 20 | 0, 1 |
| | | 7.2 | 1479–1646 | 1338–1481 | 1235–1371 | 1351–1499 | –152 | –111 | 19, 20 | 0, 1 |
| | | 10.0 | 1070–1207 | 966–1079 | 840–946 | 959–1077 | –120 | –79 | 19, 20 | 0, 1 |
| | Single triangle | 12.8 | 739–847 | 656–739 | 532–609 | 642–732 | –88 | –50 | 19, 20 | 0, 1 |
| | | 1.6 | 2471–2698 | 2214–2417 | 2235–2431 | 2307–2515 | –204 | –164 | 19, 20 | 0, 1 |
| | | 4.4 | 1925–2123 | 1734–1907 | 1680–1845 | 1780–1958 | –185 | –144 | 19, 20 | 0, 1 |
| | | 7.2 | 1440–1607 | 1297–1440 | 1195–1331 | 1311–1459 | –152 | –111 | 19, 20 | 0, 1 |
| | | 10.0 | 1025–1163 | 918–1031 | 801–907 | 915–1034 | –118 | –78 | 19, 20 | 0, 1 |
| | | 12.8 | 692–800 | 608–691 | 497–573 | 599–688 | –86 | –47 | 19, 20 | 0, 1 |
| | | 1.6 | 2117–2322 | 1917–2048 | 1447–1618 | 1827–1996 | 30 | 86 | 20 | 0 |
| | | 4.4 | 1630–1745 | 1398–1500 | 976–1123 | 1335–1456 | 27 | 111 | 19, 20 | –1, 0 |
| Virginia | Simple average | 7.2 | 1127–1272 | 948–1019 | 625–747 | 900–1013 | 61 | 112 | 19, 20 | –1, 0 |
| | | 10.0 | 776–891 | 595–636 | 389–486 | 587–671 | 38 | 89 | 19, 20 | –1, 0 |
| | | 12.8 | 482–567 | 342–360 | 225–297 | 350–408 | 24 | 70 | 19, 20 | –1, 0 |
| | | 1.6 | 2162–2367 | 1941–2072 | 1553–1736 | 1885–2058 | 24 | 76 | 20 | 0 |
| | Single sine | 4.4 | 1641–1816 | 1455–1557 | 1097–1252 | 1398–1542 | 40 | 91 | 19, 20 | –1, 0 |
| | | 7.2 | 1203–1348 | 1041–1114 | 736–865 | 993–1109 | 53 | 102 | 19, 20 | –1, 0 |
| | | 10.0 | 847–962 | 701–749 | 479–581 | 676–764 | 48 | 95 | 19, 20 | –1, 0 |
| | | 12.8 | 572–657 | 441–469 | 301–377 | 438–501 | 34 | 76 | 19, 20 | –1, 0 |
| | Single triangle | 1.6 | 2146–2351 | 1932–2064 | 1517–1696 | 1865–2037 | 27 | 80 | 20 | 0 |
| | | 4.4 | 1620–1795 | 1436–1537 | 1054–1207 | 1370–1513 | 45 | 97 | 19, 20 | –1, 0 |
| | | 7.2 | 1178–1323 | 1011–1083 | 696–822 | 962–1076 | 56 | 107 | 19, 20 | –1, 0 |
| | | 10.0 | 822–937 | 668–714 | 446–546 | 645–732 | 49 | 97 | 19, 20 | –1, 0 |
| | | 12.8 | 542–627 | 408–433 | 275–349 | 408–470 | 32 | 75 | 19, 20 | –1, 0 |

emergence in Georgia were 10°C for simple average, 12.8°C for single sine, and 12.8°C for single triangle. The least-different base temperatures and estimation methods for South Carolina were all five base temperatures for simple average, 4.4°C for single sine, and 12.8°C for single triangle. Those for Virginia were 12.8°C for simple average, 12.8°C for single sine, and 12.8°C for single triangle. Among these selected models, ones with the least difference between predicted and actual DDC were selected for each state. The most accurate state model was 12.8°C with single sine in

Georgia, 4.4°C with single sine in South Carolina, and 12.8°C with single sine in Virginia. The most frequently repeated base temperature (i.e., 12.8°C) and estimation method (i.e. single sine) from the state models were used to build a regional model. The regional DD model was 524–596 DDC estimated with the single sine method, the start date of 1 January, and base temperature of 12.8°C. The regional model predicted crawler emergence just before or within the week of actual emergence in all three states, which validated the model as good predictor.

The proposed regional model does have the shortcoming, i.e., the single sine estimation method is not easy to calculate and not commonly used. An alternative regional model may be selected by considering the estimation method and base temperature most commonly used by pest managers. A standard base temperature of 10°C (50°F) is used when the lower developmental threshold is not known for the species studied (Herms 2004). In this study, the standard base temperature of 10°C only produced accurate method using the simple average estimation method for predicting crawler emergence in Georgia. Therefore, we discourage using the standard base temperature in our regional model. The simple average is the simplest to calculate and most widely used estimation method. We recommend that the degree-day model of 411–479 DDC, estimated with the simple average method, at start date of 1 January and base temperature of 12.8°C, could be used as an alternative degree-day model for the first crawler emergence of *Parthenolecanium* spp. in the southeastern United States. This alternative degree-day model also predicted crawler emergence within the same time frame of that obtained with single sine.

The DD accumulation ranges were different from that of 1184 to 1296 DDC reported previously in Athens, GA, for *P. corni* (Hodges and Braman 2004). The corresponding dates of the DD range for crawler emergence in Athens for 2014 fell within the 22nd wk of the year while the range of DD accumulation in Griffin fell within the 19th wk of the year. Griffin is south of Athens; an earlier crawler emergence is thus expected in Griffin and therefore, the difference in DD accumulation.

The temperature data used to calculate degree-days are the major source of error in DD models (Herms 2004). If the weather station is far from the actual site or is more or less urban than the site, it may not be able to accurately record the temperature experienced by the scale insect population on the site (Schatz and Kucharik 2016). There also could be a potential effect of warmer ambient temperatures due to heat accumulation on paved surfaces in urban areas (i.e. heat islands), which benefited increased development of scale insect populations (Meineke et al. 2013). Additionally, the actual microclimate created in and around the insect body makes it virtually impossible to measure the actual temperature that the pest experiences (Herms 2004). Nevertheless, the use of weather data from standardized sources over several years tends to cancel the errors when estimating insect development (Herms 2004). Practical DD models are often developed from temperature data collected from local weather stations (Herms 2004). Predictive models based on DD accumulation such as simple average method have proven to have a practical value such as being more accurate than calendar-based schedules for timing of most management practices (Herms 2004). Hence, in a practical sense, our state and regional models should be reliable as a helping tool in predicting crawler hatching of *Parthenolecanium* spp. throughout the east coast from Georgia to Virginia.

Other variables that could influence the accuracy of degree-day estimation methods include time of the year, geographical location, and biology of the organism under study. Roltsch et al. (1999) found that single-triangle method yielded less error during the winter and early spring months in California than single-sine method. Our results suggest that the single-triangle method with 12.8°C as base temperature worked similarly to single-sine, the state and regional model, in northern sites (such as Virginia).

The phenological information and the regional and state models developed in this study are useful in planning timely scouting program for *Parthenolecanium* spp. from Georgia to Virginia. Ornamental plant producers and managers in the southeastern United States can scout for crawlers of *Parthenolecanium* spp. in

mid-April to mid-June, or more accurately predict crawler emergence with the regional model.

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References Cited

- Abd-Rabou, S., N. Ali, and M. M. El-Fatih. 2009. Life table of the hemispherical scale, *Saissetia coffeae* (Walker) (Hemiptera: Coccidae). *Egypt Acad. J. Biol. Sci.* 2: 165–170.
- Alford, D. V. 2012. Pests of ornamental trees, shrubs and flowers: a colour handbook, 2nd ed. CRC Press, Boca Raton, FL.
- Ascerno, M. E. 1991. Insect phenology and integrated pest management. *J. Arboric.* 17: 13–15.
- Babaian, G. A. 1986. Scale insects of stone fruit crops and control measures against them. *Boll. Lab. Entomol. Agrar. Filippo Silvestri.* 43 (Suppl): 133–138.
- Bailey, S. F. 1964. A study of the European fruit lecanium scale, *Lecanium corni*, on prune. *J. Econ. Entomol.* 57: 934–938.
- Baker, J. R. 1994. Lecanium scales. Ornamentals and Turf, Department of Entomology Insect Note, North Carolina State University. North Carolina Cooperative Extension Service, Raleigh, North Carolina. (<https://www.ces.ncsu.edu/depts/ent/notes/O&T/trees/note36/note36.html>) (accessed 7 June 2017).
- Bayer CropScience Chile 2014. Problemas: Conchuelas. Bayer S.A., Santiago, Chile. (<http://www.bayercropscience.cl/soluciones/problemas.asp>) (accessed 6 June 2017).
- Bellows, T. S., R. G. Van Driesche Jr., and J. S. Elkinton. 1992. Life-table construction and analysis in the evaluation of natural enemies. *Annu. Rev. Entomol.* 37: 587–614.
- Birjandi, A. K. 1981. Biology and ecology of *Parthenolecanium* spp. (Hem., Coccidae). *Entomol. Mon. Mag.* 117: 47–58.
- Birch, L. C. 1948. The intrinsic rate of natural increase of an insect population. *J. Anim. Ecol.* 17: 15–26.
- Borchsenius, N. S. 1957. Sucking Insects, vol. IX. Suborder mealybugs and scale insects (Coccoidea). Family cushion and false scales (Coccidae). *Fauna of USSR. Akademii Nauk, USSR Zoological Institute* 66: 1–493.
- Dale, A. G., and S. D. Frank. 2014a. The effects of urban warming on herbivore abundance and street tree condition. *PLoS ONE* 9: e102996. (doi: 10.1371/journal.pone.0102996).
- Dale, A. G., and S. D. Frank. 2014b. Urban warming trumps natural enemy regulation of herbivorous pests. *Ecol. Appl.* 24: 1596–1607.
- Dale, A. G., E. Youngsteadt, and S. D. Frank. 2016. Forecasting the effects of heat and pests on urban trees: impervious surface thresholds and the ‘pace-to-plant’ technique. *Arboric. Urban For.* 42: 181–191.
- Day, E. 2008. Scale insects. Virginia Polytechnic Institute and State University. Department of Entomology, Virginia Cooperative Extension, Blacksburg, VA. (http://pubs.ext.vt.edu/2808/2808-1012/2808-1012_pdf.pdf) (accessed 6 June 2017).
- Fenton, F. A. 1917. Observations on *Lecanium corni* Bouché and *Physokermes picea* Schr. *Can. Entomol.* 49: 309–320.
- García Morales, M., B. D. Denno, D. R. Miller, G. L. Miller, Y. Ben-Dov, and N. B. Hardy. 2016. ScaleNet: A literature-based model of scale insect biology and systematics. doi: 10.1093/database/bav118. (<http://scalenet.info>) (accessed 6 June 2017)
- Herms, D. A. 2004. Using degree-days and plant phenology to predict pest activity, pp. 49–59. *In* V. Krischick and J. Davidson (eds.), IPM (Integrated Pest Management) of midwest landscapes: tactics and tools for IPM. University of Minnesota, Minnesota Agriculture Experiment Station,

- Publication SB-07645, St. Paul, MN. (<http://cues.cfans.umn.edu/old/Web/049DegreeDays.pdf>) (accessed 6 June 2017)
- Hodges, G. S., and M. L. Williams. 2003. Descriptions and illustrations of the first instars of *Parthenolecanium corni* (Bouché) and *Parthenolecanium quercifex* (Fitch) (Hemiptera: Coccidae). *J. Entomol. Sci.* 38: 489–493.
- Hodges, G. S., and S. K. Braman. 2004. Seasonal occurrence, phenological indicators and mortality factors affecting five scale insect species (Hemiptera: Diaspididae, Coccidae) in the urban landscape setting. *J. Entomol. Sci.* 39: 611–622.
- Hubbard, J. L., and D. A. Potter. 2005. Life history and natural enemy associations of calico scale (Homoptera: Coccidae) in Kentucky. *J. Econ. Entomol.* 98: 1202–1212.
- Kabashima, J. N., and S. H. Dreistadt. 2014. Scales: integrated pest management for home gardeners and landscape professionals. University of California, Agriculture and Natural Resources, Statewide Integrated Management Program, Pest Notes, Publication 7408, Davis, CA.
- Kawecki, Z. 1958. Studies on the genus *Lecanium* Burm. IV. Materials to a monograph of the brown scale *Lecanium corni* Bouché, Marchal (♀ nec ♂) (Homoptera: Coccoidea: Lecaniidae). *Ann. Zool.* 4: 135–245.
- Kosztarab, M. 1959. Biological notes on the scale insects of Hungary. *Ann. Entomol. Soc. Am.* 52: 401–420.
- Kosztarab, M. 1996. Scale insects of northeastern North America: Identification, biology, and distribution. Virginia Museum of Natural History, Special Publication Number 3, Martinsville, VA.
- Kozár, F., and Y. Ben-Dov. 1997. Zoogeographical considerations and status of knowledge of the family, pp. 213–228. *In* Y. Ben-Dov and C. J. Hogson (eds.), *Soft scale insects: their biology, natural enemies and control*, vol. 7A. Elsevier Science B.V., Amsterdam, Netherlands.
- Lo, P. L. 1995. Size and fecundity of soft wax scale (*Ceroplastes destructor*) and Chinese wax scale (*C. sinensis*) (Hemiptera: Coccidae) on citrus. *New Zeal. Entomol.* 18: 63–69.
- Madsen, H. F., and M. M. Barnes. 1959. Pests of pear in California. *Calif. Agric. Exp. Stn. Circular* 478: 1–40.
- Marotta, S. 1997. General life history, pp. 251–256. *In* Y. Ben-Dov and C. J. Hogson (eds.), *Soft scale insects: Their biology, natural enemies and control*, vol. 7A. Elsevier Science B.V., Amsterdam, Netherlands.
- Marotta, S., and A. Tranfaglia. 1997. Seasonal history; diapause, pp. 343–350. *In* Y. Ben-Dov and C. J. Hogson (eds.), *Soft scale insects: their biology, natural enemies and control*, vol. 7A. Elsevier Science B.V., Amsterdam, Netherlands.
- Meineke, E. K., R. R. Dunn, J. O. Sexton, and S. D. Frank. 2013. Urban warming drives insect pest abundance on street trees. *PLoS ONE* 8: e59687.
- Meineke, E. K., R. R. Dunn, and S. D. Frank. 2014. Early pest development and loss of biological control are associated with urban warming. *Biol. Lett.* 10: 20161574.
- Meineke, E., E. Youngsteadt, R. R. Dunn, and S. D. Frank. 2016. Urban warming reduces aboveground carbon storage. *Proc. R. Soc. Lond. [Biol.]* 283: 20161574.
- Mussey, G. J., and D. A. Potter. 1997. Phenological correlations between flowering plants and activity of urban landscape pests in Kentucky. *J. Econ. Entomol.* 90: 1615–1627.
- (OSU) Oregon State University 2016. Online phenology and degree-day models for agricultural and pest management decision making in the US. Oregon State University, Integrated Plant Protection Center, Corvallis, OR. (<http://uspest.org/cgi-bin/ddmodel.us>) (accessed 6 June 2017).
- Parmesan, C., and G. Yohe. 2003. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* 421: 37–42.
- Podoler, H. I., R. Bar-Zacay, and D. Rosen. 1979. Population dynamics of the Mediterranean black scale, *Saissetia oleae* (Olivier), on citrus in Israel. 1. A partial life table. *J. Entomol. Soc. South Afr.* 42: 257–266.
- Rainato, A., and G. Pellizzari. 2009. Observations on the biology of *Parthenolecanium rufulum* in northeastern Italy, with a redescription of the first and second instar females. *Bull. Insectol.* 62: 85–91.
- Raupp, M. J. 1985. Monitoring: An essential factor to managing pests of landscape trees and shrubs. *J. Arboric.* 11: 349–355.
- Raupp, M. J., C. S. Koehler, and J. A. Davidson. 1992. Advances in implementing integrated pest management for woody landscape plants. *Annu. Rev. Entomol.* 37: 561–585.
- Robayo Camacho, E., and J. H. Chong. 2015. General biology and current management approaches of soft scale pests (Hemiptera: Coccidae). *J. Integr. Pest. Manage.* 6: 1–22.
- Roitsch, W. J., F. G. Zalom, A. J. Strawn, J. F. Strand, and M. J. Pitcairn. 1999. Evaluation of several degree-day estimation methods in California climates. *Int. J. Biometeorol.* 42: 169–176.
- Sanders, J. G. 1909. The identity and synonymy of some of our scale insects. *J. Econ. Entomol.* 2: 428–448.
- Santas, L. A. 1985. *Parthenolecanium corni* (Bouché) an orchard scale pest producing honeydew foraged by bees in Greece. *Entomol. Hell.* 3: 53–58.
- SAS Institute Inc 2011. Base SAS® 9.3. Procedure's Guide. Statistical Procedures. SAS Institute Inc., Cary, NC.
- Schatz, J., and C. J. Kucharik. 2016. Urban heat island effects on growing seasons and heating and cooling degree days in Madison, Wisconsin USA. *Int. J. Climatol.* 36: 4873–4884.
- Schultz, P. B. 1984. Natural enemies of oak lecanium (Homoptera: Coccidae) in eastern Virginia. *Environ. Entomol.* 13: 1515–1518.
- Schultz, P. B. 1985. Monitoring parasites of the oak lecanium scale with yellow sticky traps. *J. Arboric.* 11: 182–184.
- Southwood, T.R.E., and P. A. Henderson. 2000. *Ecological methods*, 3rd ed. Blackwell Science, Oxford, United Kingdom.
- Swiecki, T. J., and E. A. Bernhardt. 2006. A field guide to insects and diseases of California oaks. General Technical Report PSW-GTR-197, United States Department of Agriculture, Forest service, Pacific Southwest Research Station, Albany, CA.
- Townsend, L. 2005. Lecanium scales. Cooperative Extension Service, University of Kentucky, College of Agriculture, Entfact 430. Lexington, Kentucky. (<https://entomology.ca.uky.edu/files/efpdf2/ef430.pdf>) (accessed 6 June 2017).
- Washburn, J. O., and L. Washburn. 1984. Active aerial dispersal of minute wingless arthropods: exploitation of boundary-layer velocity gradients. *Science* 223: 1088–1089.
- Williams, M. L., and G. S. Hodges. 1997. Taxonomic characters – nymphs, pp. 143–156. *In* Y. Ben-Dov and C. J. Hogson (eds.), *Soft scale insects: their biology, natural enemies and control*, vol. 7A. Elsevier Science B.V., Amsterdam, Netherlands.
- Williams, M. L., and M. Kosztarab. 1972. Morphology and systematics of the Coccidae of Virginia with notes on their biology (Homoptera: Coccoidea). *Res. Div. Bull. Virginia Polytech. Inst. State Univ.* 74: 1–215.