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Seasonal Occurrence and Development of Degree-Day Models for Predicting Activity of *Conotrachelus nenuphar* (Coleoptera: Curculionidae) in Alabama Peaches

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ABSTRACT The plum curculio, *Conotrachelus nenuphar* (Herbst) (Coleoptera: Curculionidae), is a key pest of peaches, *Prunus persica* (L.) Batsch, in North America. Captures of adult weevils in unbaited pyramid traps recorded annually from 2000 to 2008 in an unmanaged peach orchard in central Alabama were used to determine its seasonal occurrence and to develop predictive degree-day models. Spring migration of plum curculio began at bloom (early to mid-March). Linear, polynomial, and three-parameter Weibull functions were tested to describe the relationship between weekly trap capture and cumulative degree-day (DD). Criteria used to select the best models were the smallest Akaike information criterion and highest R^2 values. A sixth-order polynomial function fitted best to seasonal trap captures and cumulative DDs and revealed two major seasonal peaks with the first (spring generation) and second (summer generation) peaks occurring at cumulative DDs of ≈245 and 1105 (base 10°C, biofix of 1 January), respectively. A potential third (late summer generation) peak was observed at 1758 DDs. The sixth-order polynomial model predicted the first trap capture to occur at cumulative DD of ≈99 (base 10°C, biofix of 1 January). The three-parameter Weibull model predicted the first trap and first peak (spring generation) trap captures to occur at mean cumulative DDs of 108.02 ± 9 and 220.07 ± 16, respectively. Validation of the models in the unmanaged orchard in 2009 and 2010 and in a second unmanaged orchard (located 1.6 km from the first) in 2009 showed that the polynomial and Weibull were within ±7 d in their predictions of the first and peak trap captures of the spring population. Validation results showed that both models successfully predicted the first trap capture in one out of three scenarios and the peak trap capture in two out of three scenarios. The performance of the models is discussed in relation to management of plum curculio in central Alabama.

KEY WORDS degree-day models, biofix, plum curculio, Weibull function, polynomial function

Plum curculio, *Conotrachelus nenuphar* (Herbst) (Coleoptera: Curculionidae), is a major pest of many stone and pome fruit crops and is widely distributed across the United States and Canada, east of the Rocky Mountains (Chapman 1938, Armstrong 1958). In the southern United States, plum curculio typically overwinters as adults in wooded lots adjacent to peach, *Prunus persica* (L.) Batsch, orchards from where they immigrate into the orchards in the spring beginning around bloom (Snapp 1940, Yonce et al. 1995, Johnson et al. 2002a). Development and activity of plum curculio, including spring migration, is greatly influenced by field conditions such as temperature, rainfall (amount and timing), humidity, and wind speed (Whitcomb 1932, Dixon et al. 1999). In the southern United States and most parts of North America, management of plum curculio is achieved mainly by the use of insecticides because no alternative control is currently effective. For example, Alabama peach growers typically apply six to 12 calendar-based sprays of broad-spectrum organophosphate insecticides, pyrethroid insecticides, or a combination per growing season to control plum curculio (Foshee et al. 2008). A recent study by our program suggests that three to four targeted insecticide sprays may provide a cost-effective and environmentally sound alternative to the calendar-based spray program for plum curculio (unpublished). However, the success of a targeted spray management strategy is highly dependent on the ability to effectively detect and predict the activity of plum curculio in the orchards, so that insecticide sprays can be properly timed to coincide with the period of peak abundance and activity of the pest.

Models based on linear and nonlinear functions have been used to predict key insect events such as time of egg hatch, larval and pupal developmental times in the laboratory, and the first and peak trap

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captures and time of diapause in the field (Welch et al. 1981, Higley et al. 1986, Doerr et al. 2002, Blanco and Hernandez 2006, Broatch et al. 2006). Several predictive models such as degree-day models have been used to make important orchard pest management decisions with varying degrees of success (Dent 2000, Blanco and Hernandez 2006, Broatch et al. 2006). The concept of degree-days (DD) is that heat units accumulated over a 24-h period above a temperature developmental threshold could be used to predict insect development and activity patterns over time because temperature is the most important abiotic factor that affects the development of insects (Potter 1981, Higley et al. 1986).

Although DD models can provide proper timing of specific insect events, these temperature-dependent models are not currently available for many species. To date, the only plum curculio DD model developed and applied at grower level is the oviposition model, which relates temperature (cumulative heat units) to cumulative fruit injury for scheduling insecticide applications against plum curculio in New York apples (*Malus* spp.) (Reissig et al. 1998). However, this model has had limited use in peaches in the southeastern region due to the potential errors associated with extending insect phenology data from crop to crop or region to region without validation (Pitcairn et al. 1992, Hoffmann et al. 2004). Hence, a DD model to predict the emergence of adult plum curculio in peaches is necessary to improve the timing of insecticides against plum curculio in Alabama and other parts of the southeastern United States.

Developing a DD model for an insect requires an appropriate biofix, defined as the date to begin accumulation of DDs (Flint and Gouveia 2001), and temperature developmental thresholds which consist of a lower and upper threshold (Flint and Gouveia 2001, Blanco and Hernandez 2006, Diaz et al. 2007). For most insects, including plum curculio, the lower and upper developmental thresholds are usually ≈10°C and 35°C, respectively (Johnson et al. 2002a, Lan et al. 2004), and a biofix of 1 January is typically used in most parts of the United States (Hoffmann et al. 2004, Piñero and Prokopy 2006). However, because field conditions are variable and the development of insects can be influenced by microclimatic factors, population genetics, and host quality (Pitcairn et al. 1992), biofixes and temperature developmental thresholds used to determine DD requirements for insects could vary among different ecosystems. Temperature developmental thresholds are typically developed in the laboratory, but their application in the field is usually limited because the DD requirements of insects may vary between laboratory and field (Hagstrum and Hagstrum 1970, Taylor and Shields 1990).

In this study, captures of plum curculio adults in unbaited pyramid traps recorded annually from 2000 to 2008 in an unmanaged peach orchard in central Alabama were used to determine the seasonal occurrence of the pest and to develop predictive DD models for critical decision making on the timing of insecticide applications against plum curculio in Alabama peach orchards.

Materials and Methods

Study Location. Trap captures data used in this study were collected at a 0.07-ha unmanaged mixed variety peach block (referred herein as orchard) at the Chilton Research and Extension Center (CREC), Clanton (32° 50′23″ N, 86° 37′41″ W), AL, from 2000 to 2008 (nine peach growing seasons). The orchard had been used previously to evaluate different peach rootstocks and contained remnants of trees of several peach varieties such as 'Nemaguard', 'Hagler', 'Rutgers Redleaf', 'Lovell', and 'Elberta'. The orchard had not received any insecticide or fungicide application since its establishment in 1985; thus, high plum curculio populations had historically been recorded at the orchard. Routine maintenance was done by removal of dead tree branches and weeding with a mower mounted on a tractor. In all years, fruit were not harvested but allowed to remain on the trees until they dropped.

Seasonal Occurrence of Plum Curculio. Captures of plum curculio adults in four unbaited pyramid traps installed at random locations along the periphery of the orchard from 2000 to 2008 were used to determine seasonal occurrence. Trap placement procedures were as described by Prokopy and Wright (1997) and Akotsen-Mensah et al. (2010). All traps were installed in the orchard by 28 February of each year and were removed at the end of the seasonal activity of plum curculio, usually ≈5 August. Traps were checked two to three times per week for plum curculio adults. Trap count data were pooled to obtain weekly trap captures with Fridays as the end of the week. This means that all trap captures from Saturday through Friday of each week were recorded as Friday trap counts. Degree-day data were handled the same way. The data obtained were then used to determine the seasonal occurrence. The following events were recorded yearly: first and peak trap captures of plum curculio, total number of plum curculios captured during the entire season, and phenology of peach trees.

Determination of Biofix and Lower Temperature Threshold (LTT) for Accumulation of Degree-Days. To determine the best biofix and LTT for accumulating DDs in peach orchards, seven sets of biofixes and four potential LTTs with no upper temperature threshold (UTT) were used to calculate cumulative DDs using historic weather data obtained from the Alabama Mesonet database for Thorsby, AL (http://www.awis.com/cgi-bin/uncgi/awondasta.uncgi) and the National Weather Service, Raleigh, NC (http://www.weather.gov/climate). The biofixes evaluated were 1 January, 15 January, 1 February, 15 February, 1 March, first plum curculio trap capture, and average temperature of >12°C occurring for three consecutive days. Cumulative DDs were calculated for each of these biofixes at LTTs of 7.2°C (45°F), 10°C (50°F), 11.1°C (52°F), and 12.8°C (55°F). These biofixes and LTTs were selected because they have been used in other studies to accumulate DDs (Mulder et al. 1997, Mulder and Stafne 1998, Johnson et al. 2002b, Hoffmann et al. 2004, Piñero and Prokopy 2006). No UTT was used because examination of the historic maximum temperatures available to us showed that maximum temperatures within the period of the spring migration did not exceed the UTT of 35°C reported for plum curculio (Lan et al. 2004). In all cases cumulative DDs were calculated using the simple average method given by $DD = \Sigma(T_i - LTT)$, where DD is degree-day; T_i is the mean daily temperature on day I, and LTT is the base temperature. The few instances where temperatures were negative during the calculation of the DDs were assigned zero. To establish the best biofix and LTT combination, a coefficient of variation (CV), which is a measure of variability within random sampling, was calculated for each of the observed cumulative DDs at which a plum curculio event such as first and peak trap capture occurred during the spring of each year. The coefficient of variation is the most commonly used method for measuring variability and was calculated by dividing the mean cumulative DD at each biofix and LTT over the entire 9-yr period by the SD. The two most promising biofixes and LTTs, which produced the lowest coefficient of variation were selected and used to calculate the DDs. The cumulative DDs calculated from the two promising biofixes and LTTs were used for the models to predict the first and peak trap captures.

Models to Predict the First and Peak Trap Captures of Plum Curculio. *Models to Predict Seasonal Peaks.* Several models were evaluated to predict the seasonal peak trap captures of plum curculio. This was done by fitting the weekly trap captures (dependent variable) and cumulative DDs (independent variable) calculated by using the appropriate biofixes and LTTs obtained as described above for the 2000–2008 data, whereas the 2009 and 2010 data were used to validate the models. Due to year-to-year variability in population numbers, the weekly trap capture data were normalized within each year by calculating the proportion of weekly trap capture of the total trap capture within the year. Linear, quadratic, cubic, and fourth–sixth order polynomial functions were then fitted to the normalized trap capture data and the cumulative DD to generate parameter estimates for both biofixes (1 and 15 January) and base temperatures of 7.2 and 10°C by using the JMPIN, version 7.0.1 (SAS Institute 2007). For each function, an Akaike Information Criterion (AIC) (Akaike 1974, Bozdogan 1987) and coefficient of determination (R-square), which are usually used to assess and evaluate statistical models, were generated using the R package (R Development Core Team 2009) and subsequently used to select the best model that fitted well to the weekly trap captures and cumulative DD data. Also, a fitted curve was generated for the best model using SAS software (JMPIN, version 7.0.1). The first-order derivative of the equation relating the dependent and independent variables of the selected model was used to determine the maximum peaks that represented the function that best described the overall seasonal peaks (both spring and summer generation) of plum curculio. The values of the first and peak trap captures were calculated from the best model using Excel, version 2007 (Microsoft, Redmond, WA).

Three-Parameter Weibull Function to Predict First and Peak Trap Captures of Spring Population. To confirm the peak of the spring population (first peak), which is very crucial for managing plum curculio with insecticide application, a three-parameter Weibull function was fitted to the proportion of plum curculio captured during spring of each year as a function of cumulative DD from 2000 to 2008 to predict the first and peak trap captures by using SigmaPlot, version 8.0 (Systat Inc. 2002). The three-parameter Weibull function was selected because its parameters α and β, represent the expected normalized DD at onset of first migration and the estimate of the first peak trap capture of plum curculio, respectively. Also, the three-parameter Weibull function has been used to determine the relation between DDs and several events in insects (Collier and Finch 1985, Broatch et al. 2006) and some plants (Martinson et al. 2007, Royo-Esnal et al. 2010). The three-parameter Weibull function is represented by the equation 1 below:

$$Y = 1 - \exp\left((-(DD - \alpha)/\beta)^{\gamma}\right) \quad [1]$$

where Y represents the cumulative proportion of plum curculio trap capture over the entire spring generation period as related to the accumulated DD. In this equation, α is constant for rate of migration of the spring generation, which is the estimate of the first trap capture; β is the estimate of the peak trap capture expected normalized time (degree-day) of the spring generation; and γ is the rate of the immigration of the spring generations. The coefficient of determination (R^2) was used to judge the goodness-of-fit of each parameter estimated by the Weibull function. The model for each trap capture event such as first and peak trap captures was evaluated for each year by comparing the observed and predicted DDs. This was done to determine the ability of the Weibull function to model its own source data. For this, it was assumed that where the difference between the observed and predicted DDs did not exceed ±56 DDs the model was considered to be accurate within ±7 d. We used 56 DDs because the average DD per day during the period of the spring migration in the study area was ≈8 (base 7.2 and 10°C). Thus, because the trap captures and DD were done every week, the cumulative DD for each predicted in theory occurred within a week. A negative DD difference between observed and predicted values indicated that the observed event occurred before predicted date and a positive difference indicated the event occurred after the predicted date.

Model Validation. The DD models obtained from the 2000–2008 data were validated using 2009 and 2010 data in the same unmanaged orchard where the seasonal occurrence data were collected. Validation also was conducted on data sets collected from a second unmanaged peach orchard in 2009. This orchard is located ≈1.6 km from the first orchard and consisted primarily of the 'Loring' peach variety. Use of a sep-

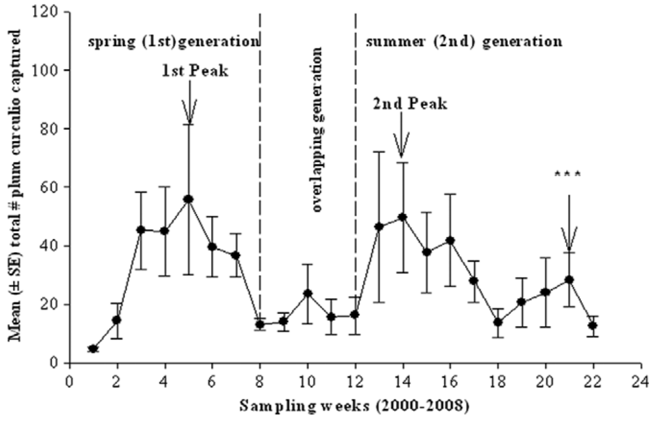

Fig. 1. Seasonal occurrence of plum curculio in an unmanaged peach orchard in Clanton, AL, during the 2000–2008 peach growing seasons. Figure shows combined mean ± SE) for all nine years. *** indicates potential third minor peak.

arate orchard for the validation allowed us to generate a data set that is independent of the data used to generate the DD model. Methods used to obtain data from the validation orchard were similar to those described previously. The observed cumulative DDs at which first and peak trap captures occurred during the validation period were recorded using the simple average method described above. The observed cumulative DDs for the first and peak trap captures were compared with the model prediction of these events using both the polynomial and Weibull functions for the 2000–2008 data. The difference between the observed and predicted was used to judge whether the models were accurate in predicting the first and peak plum curculio trap captures. In addition, Pearson's correlation coefficient tests were performed on the observed and predicted DD to determine the association between the two variables for the entire season.

Results

Seasonal Occurrence of Plum Curculio. The first captures of plum curculio were recorded as early as the week of 3–10 March (2000) and as late as the week of 14–20 March (2001, 2005, and 2008). Total capture of plum curculio adults for all traps pooled from 2000 to 2008 was 5,162, with a mean ± SE of 516.2 ± 135.8 adults per four trap per observation year. Overall, plum curculio's migration began when peach trees in the orchard were at varying developmental stages depending on the variety (i.e., at bloom stage for early maturing varieties, pink stage for some mid-season and late-maturing varieties). No plum curculio was captured before bloom. Plum curculio trap captures varied by year, but the seasonal occurrence observed throughout the 9-yr period (2000–2008) followed a similar pattern (Fig. 1). The population of the spring generation was sustained but gradually declined after week 8 (Fig. 1). The data indicated an overlap of the spring and summer generations. This was confirmed by the additional data collected from sampled females from weeks 7 to 15 to determine their egg developmental stage. Approximately 80% or more of the females had no or early development oocytes from weeks 7 to 15, indicative of the presence of newly emerged adults during this period (unpublished data). The summer generation peak was recorded approximately week 14 (15 June). A potential third (late summer) generation peak was recorded approximately week 21 (29 July) (Fig. 1).

Determination of Biofix and Lower Temperature Threshold for Accumulation of Degree-Days. The coefficient of variation of the accumulated DDs at the various biofixes increased as the LTTs increased (Fig. 2). The coefficient of variation determined for the biofixes and LTTs showed that 1 January at LTT of 10°C and 15 January at LTT of 7.2°C produced the lowest coefficient of variation values for accumulation of DDs at which both the first (Fig. 2A) and peak trap (Fig. 2B) captures of the spring population occurred. These biofixes and LTTs were subsequently selected and used to calculate all DDs and to determine the models for predicting plum curculio seasonal activities. For comparison, the biofix of 1 January (Piñero and Prokopy 2006) and LTT of 10°C (Reissig et al. 1998, Hoffmann et al. 2004) also have been used to calculate DD.

Polynomial Functions to Predict Seasonal Peaks. Among the several polynomial functions evaluated using biofixes of 1 January and 15 and LTTs of 7.2 and 10°C, a sixth-order polynomial (equation 2 [see below] produced the best fit with the least AIC of −1034.7 and highest R^2 of 0.184 (Table 1). The data of 1 January and LTT of 10°C were selected as the best combination, and data calculated using these were used to generate the polynomial function (equation 2). All the order terms in the sixth-order polynomial function that described the relationship between the seasonal trap captures (2000–2008; number of sampling weeks = 171) and cumulative DD by using a biofix of 1 January and LTT of 10°C were significant ($P < 0.0001$) (Table 2). The polynomial function predicted that plum curculio has two major peaks and a potential minor third peak, based on product mathe-

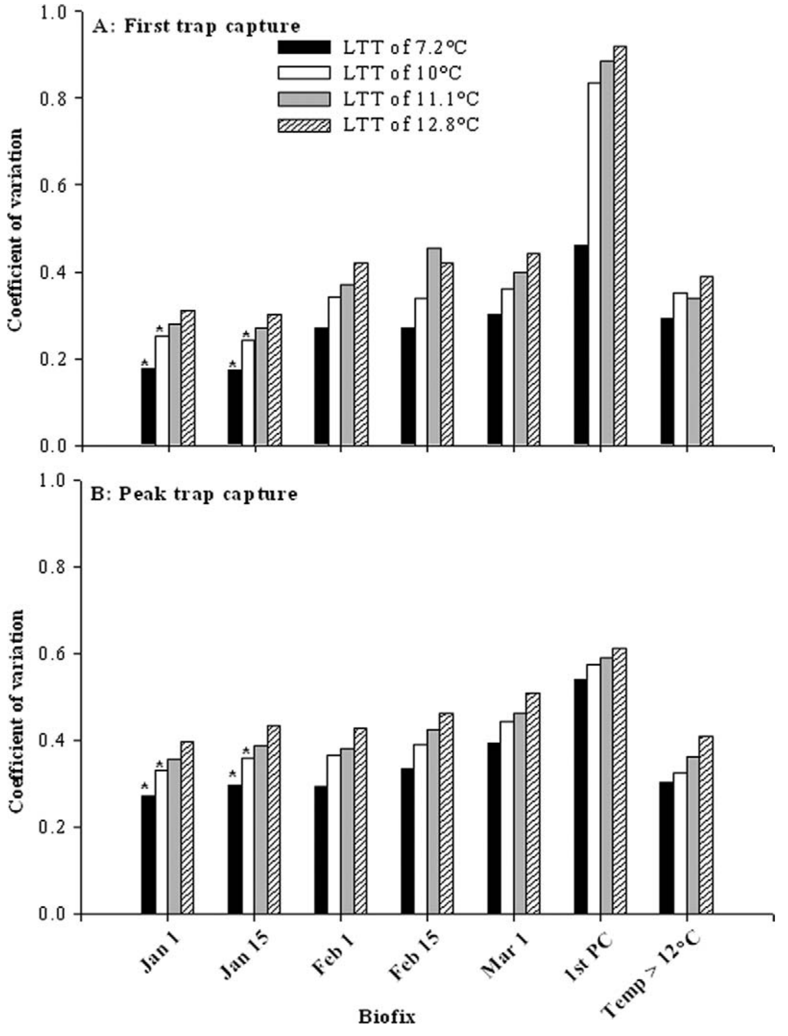

Fig. 2. CV calculated for different biofixes and LTTs for first plum curculio trap capture (A) and first peak trap capture of the spring population (B) during 2000–2008. * denotes values with low CVs chosen to calculate all DD used for the DD model.

matics (Fig. 3). The first (spring generation), second (summer generation), and potential third (late summer generation) peak trap captures occurred at accumulated DDs of ≈245.84, 1105.44, and 1758.21 (biofix at 1 January and LTT of 10°C), respectively (Fig. 3). There was a significant effect of intercept ($t = -2.74$, $P = 0.0069$), indicating that the cumulative DD at which plum curculio started migrating into the orchard was significantly different than zero (Table 2).

Table 1. AIC and coefficient of determination for assessment and selection of the best model

Equation	LTT 7.2°C				LTT 10°C			
	Biofix Jan 1		Biofix Jan 15		Biofix Jan 1		Biofix Jan 15	
	AIC	R^2	AIC	R^2	AIC	R^2	AIC	R^2
Linear	−1008.0	0.019	−1008.0	0.019	−1008.0	0.019	−1008.0	0.019
Quadratic	−1007.9	0.024	−1007.6	0.022	−1007.9	0.024	−1007.6	0.022
Cubic	−1008.5	0.033	−1009.3	0.036	−1008.9	0.035	−1009.3	0.038
Fourth-order polynomial	−1006.7	0.028	−1007.5	0.030	−1006.9	0.029	−1007.5	0.033
Fifth-order polynomial	−1023.0	0.122	−1019.5	0.125	−1019.2	0.102	−1019.5	0.104
Sixth-order polynomial	−1033.6	0.170	−1034.7	0.183	**−1034.7**	**0.184**	**−1034.7**	**0.184**

Bold indicates model with the smallest AIC and highest coefficient of determination (R^2) selected as best polynomial model.

Table 2. Parameter estimates for fit of sixth-order polynomial model to determine peaks of plum curculio trap capture during 2000–2008 peach seasons in an unmanaged peach orchard in Clanton, AL

Order of term in equation	Parameter estimate	SE	t-ratio	Prob. > $\|t\|$
Intercept	−0.079207	0.02893	−2.74	0.0069
DD10	0.0001523	3.66e−05	4.16	<0.0001
$(DD10\text{-}754.046)^2$	3.3804e−07	8.01e−08	4.22	<0.0001
$(DD10\text{-}754.046)^3$	−1.1823e−09	2.43e−10	−4.86	<0.0001
$(DD10\text{-}754.046)^4$	−4.191e−13	1.72e−13	−2.44	0.0157
$(DD10\text{-}754.046)^5$	2.095e−15	4.12e−16	5.09	<0.0001
$(DD10\text{-}754.046)^6$	−9.999e−19	2.42e−19	−4.13	<0.0001

$Y = -0.079207 + 0.0001523 \times DD_{10} + 3.3804e{-7} \times (DD_{10} - 754.046)^2 - 1.1823e{-9} \times (DD_{10} - 754.046)^3 - 4.191e{-13} \times (DD_{10} - 754.046)^4 + 2.095e{-15} \times (DD_{10} - 754.046)^5 - 9.999e{-19} \times (DD_{10} - 754.046)^6$.

DD_{10} is degree-day calculated using biofix of 1 January and a base temperature of 10°C.

$$Y = -0.079207 + 0.0001523 \times DD_{10} + 3.3804e{-7} \times (DD_{10} - 754.046)^2 - 1.1823e{-9} \times (DD_{10} - 754.046)^3 - 4.191e{-13} \times (DD_{10} - 754.046)^4 + 2.095e{-15} \times (DD_{10} - 754.046)^5 - 9.999e{-19} \times (DD_{10} - 754.046)^6 \quad [2]$$

where Y is the normalized proportion of yearly trap capture, and DD is the cumulative degree-day calculated using biofix of January and LTT of 10°C.

Three-Parameter Weibull Function to Predict First and Peak Trap Captures of Spring Generation. The predicted cumulative distributions of plum curculio trap captures versus cumulative DDs by using the three-parameter Weibull function is shown in Fig. 4. The summary of the best fit and mean ± SE parameter estimates showed that the first trap capture (α) is predicted to occur at accumulated DD of 210.3 ± 14 (biofix of 1 January) and 222.1 ± 12 (biofix of 15 January) at LTT of 7.2°C ($P < 0.0001$) (Table 3). Also the best fit and parameter estimates for the first trap capture is predicted to occur at a mean accumulated DDs of 108.5 ± 10 (biofix of 1 January) and 78.0 ± 9 (biofix of 15 January) at LTT of 10°C ($P < 0.0001$) (Table 3).

The three-parameter Weibull model also predicted the first peak trap capture (β) to occur at accumulated DDs at the different biofixes and LTTs as follows: 339.6 ± 23 (biofix of 1 January and LTT 7.2°C; $P < 0.0001$); 244.9 ± 20 (biofix of 15 January and LTT 7.2°C; $P < 0.0001$); 220.1 ± 16 (biofix of 1 January and LTT 10°C; $P < 0.0001$); and 171.0 ± 14 (biofix of 15 January and LTT 10°C; $P < 0.0001$) (Table 3).

The coefficient of determination for each of the parameters of the Weibull function that predicted the DD was >80%, indicating that the model parameters explained most of the variability within the data used to generate the model.

Comparing the observed and predicted DDs on year-by-year basis for the first trap capture by using the three-parameter Weibull function, 1 and 15 January and at both LTTs of 7.2 and 10°C showed 77.8% in the ability of the model to accurately predict its own source data for the first trap capture within a 7-d (56 DD) window (Table 4). In contrast, the model, at the biofixes of 1 and 15 January and at LTT of 7.2°C, was only able to accurately predict the peak trap capture of its own source data by 44.4% within the 7-d (56 DD) window (Table 4). Also, the biofixes of 1 January and 15 at LTT of 10°C predicted their own source data successfully by 55.6 and 66.7%, respectively (Table 4). Based on the overall performance of the Weibull model, the results showed that the LTT of 10°C and 1 January and 15 biofixes were better in simultaneously predicting the first and peak trap captures within the 7-d (56 DD) window (Table 4). The Weibull model also predicted the cumulative DD at 25, 50, 75, and 95% of trap captures of spring generation of plum curculio to occur at 168, 252, 396, and 731, respectively (Table 5).

Validation of Degree-Day Model. The results of the validation tests for the sixth-order polynomial and the three-parameter Weibull functions by using data sets from the same unmanaged orchard in 2009 and 2010 and a second unmanaged orchard (Loring) in 2009 are shown in Table 5. The results showed that both models

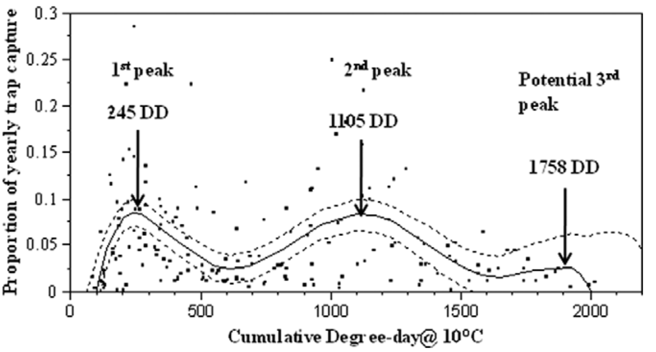

Fig. 3. Polynomial fit of the seasonal peak trap captures of plum curculio to cumulative degree-day at base 10°C by using 1 January as biofix (2000–2008; $n = 171$) in an unmanaged peach orchard in Clanton, AL. Dark trend line indicates predicted seasonal trend. Dotted lines show confidence interval around the predicted seasonal trend. Arrows show predicted peaks.

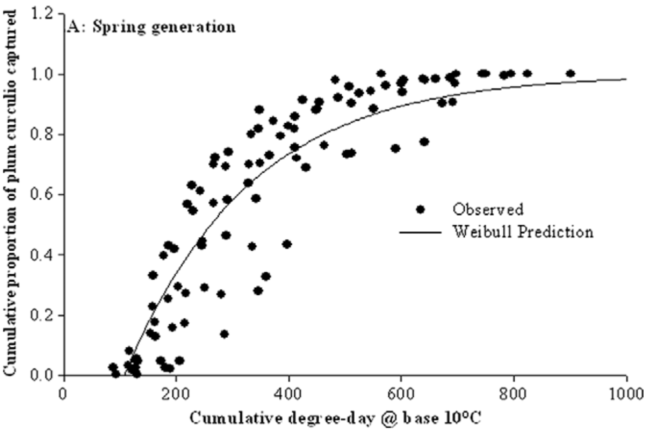

Fig. 4. Three-parameter Weibull model relating the proportion of adult plum curculio (spring generation) captured in traps versus cumulative degree-day at base 10°C and biofix of 1 January during the 2000–2008 peach growing seasons.

were able to predict the first trap capture in one out of three scenarios and the peak trap capture in two out of three scenarios in which the models were validated at biofix of 1 January at LTT of 10°C. The Pearson's correlation coefficients of the observed and predicted DDs for the entire season by using data generated from the polynomial function were only significant in the first unmanaged orchard in 2009 ($R = 0.623$, $P = 0.0043$) but not in 2010 ($R = 0.491$, $P = 0.5528$) and also were not significant in the second unmanaged orchard in 2009 ($R = 0.343$, $P = 0.5859$). In addition, the correlation coefficients of the observed and predicted DDs using the Weibull model (spring generation) were significant in the first unmanaged orchard in 2009 ($R = 0.604$, $P = 0.0491$) and 2010 ($R = 0.698$, $P = 0.0366$) but not in the second unmanaged orchard in 2009 ($R = \infty$).

Discussion

The results of this study showed that migration of plum curculio into peach orchards during spring is predictable using degree-days. Seasonal migration of overwintered plum curculio adults into peach orchards began in early to mid-March when peaches were at varying developmental stages depending on the variety (i.e., at bloom stage for early maturing varieties, pink stage for midseason, and late maturing varieties). The population of the spring generation was sustained but gradually declined until the beginning of the emergence of the summer generation (late May to early June). The data indicated an overlap of the spring and summer generations. This was supported by results from samples of females examined for stage of egg development between weeks 7 to15 (unpublished data). The early March to early June period in central Alabama, when plum curculio trap numbers were high, is usually associated with steady but fluctuated increases in air and soil temperatures, with relatively high humidity. These conditions are conducive for adults to begin their migration either by flying or walking to the trees (Prokopy and Wright 1997, Prokopy et al. 1999). Our results on the seasonal occurrence and onset of spring migration of plum curculio into peach orchards are similar to those reported in peaches in nearby Georgia (Yonce et al. 1995). Similar results also were obtained in apples in New York (Chapman 1938) and Quebec, Canada (Lafleur and Hill 1987) and in New Jersey blueberries (*Vaccinium* spp.) (Polavarapu et al. 2004).

Based on the estimation of coefficient of variations, 1 January at LTT of 10°C and 15 January at LTT of 7.2 were the most accurate biofix and LTT combinations for accumulation of DDs in a peach orchard in central Alabama. However, 1 January at LTT of 10°C was selected as the most accurate combination to accumulate DD for modeling both the first and peak trap captures based on results from the model assessment tools such as the AIC and R^2. The practicality of this combination (1 January at LTT of 10°C) is also an important factor, because 1 January is a relatively easier date to remember by growers who are the ultimate users of the DD model. Furthermore, growers can obtain DD values at this biofix and LTT from

Table 3. Best fit and mean ± SE parameter estimates of the three-parameter Weibull model for predicting first and peak trap captures of spring population of plum curculio at different LTTs and biofixes

Parameter	LTT 7.2°C		LTT 10°C	
	Biofix 1 Jan.	Biofix 15 Jan.	Biofix 1 Jan.	Biofix 15 Jan.
α	210.3 ± 14	222.1 ± 12	108.5 ± 10	78.0 ± 9
β	339.8 ± 23	244.9 ± 20	220.1 ± 16	171.0 ± 14
γ	1.0 ± 0.5	1.0 ± 0.2	1.0 ± 0.5	1.0 ± 0.8
R^2	83.3	84.1	84.1	79.6
F	243.5	302.8	255.7	189.9
P α and β	<0.0001	<0.0001	<0.0001	<0.0001

α is predicted cumulative degree-day at first plum curculio trap capture for each year from 2000 to 2008. β is predicted cumulative degree-day at peak trap capture. γ is the rate of trap capture ($P = 0.05$). R^2 is coefficient of determination. df = 2, 113.

$Y = 1 - \exp((-(DD - \alpha)/\beta)^{\gamma})$.

Table 4. Comparison of observed and predicted first and peak plum curculio trap captures by using the three-parameter Weibull model

Yr	First trap capture				Peak trap capture			
	LTT 7.2°C		LTT 10°C		LTT 7.2°C		LTT 10°C	
	Obs.-Pred. 1 Jan.	Obs.-Pred. 15 Jan.	Obs.-Pred. 1 Jan.	Obs.-Pred. 15 Jan.	Obs.-Pred. 1 Jan.	Obs.-Pred. 15 Jan.	Obs.-Pred. 1 Jan.	Obs.-Pred. 15 Jan.
2000	99.2	**12.2**	81.9	66.0	**11.7**	**31.5**	**−3.0**	**0.1**
2001	**32.8**	**14.7**	**13.7**	**43.7**	138.4	227.1	68.9	118.0
2002	**−30.9**	**−53.1**	**−19.7**	**6.7**	−72.7	**11.8**	−62.3	**−16.8**
2003	**19.1**	**−6.1**	**9.0**	**35.6**	**48.5**	130.0	**7.5**	**53.2**
2004	**−33.8**	−88.7	**−14.7**	**−10.6**	**−8.7**	**43.2**	**−24.0**	**−0.9**
2005	**34.4**	−78.3	**22.6**	**−9.9**	73.8	67.8	**22.8**	**9.3**
2006	**36.0**	**−39.5**	**19.8**	**16.2**	317.6	348.8	210.3	225.8
2007	70.3	**−2.9**	64.9	56.5	171.8	205.3	125.4	136.0
2008	**13.3**	**−36.5**	**7.0**	**14.0**	**−13.1**	**43.8**	**−34.5**	**−8.5**
Predicted (2000–2008)[a]	210. 3 ± 14	222.1 ± 12	108.0 ± 10	78. 0 ± 9	339.8 ± 23	244.9 ± 20	220.1 ± 16	171.0 ± 14
Percentage success[b]	77.8	77.8	77.8	77.8	44.4	44.4	55.6	66.7

$Y = 1 - \exp\left(-DD - \alpha)/\beta\right)^{\gamma}$).

[a] Overall prediction using the 2000–2008 data (number of sampling weeks = 171). Bold indicates the difference between observed and predicted cumulative degree-days for specific plum curculio event within ±7 d (based on daily average degree-day accumulation of approximately eight during spring migration).

[b] Percentage of number of years in which observed did not differ from predicted within ±7 d when daily average degree-day accumulation was approximately eight during the spring migration.

several weather service providers within their locality at reasonable or no cost (Flint and Gouveia 2001). In addition, some studies have already used this biofix with some degree of accuracy and thus will allow comparison of our results with other studies (Reissig et al. 1998, Piñero and Prokopy 2006).

Among the polynomial functions evaluated the sixth-order polynomial function predicted two major peaks and a potential third peak for plum curculio. Two major peaks also have been reported for plum curculio in other regions (Snapp 1940, Horton and Ellis 1989, Lan et al. 2004, Leskey 2008). Although the potential third peak (occurring around 29 July, referred to as late summer generation) was established by product mathematics, it is likely to have some biological significance because of the seasonality of plum curculio and the temperatures typically recorded during late summer in central Alabama. First, examination of our data showed that the females of the spring and summer generations began to lay eggs usually in early to mid-April and mid-June, respectively. In 2010, for example, the first egg was deposited on 13 April (191 DD at biofix of 1 January and LTT of 10°C) and the peak of the summer generation trap capture occurred on 26 June (1209 DD). The difference in DD between these two events is 1018. The mean ± SD daily cumulative DD for the same period was 13.7 ± 4.1. Therefore, the number of days that plum curculio completed its development from egg to peak trap capture in 2010 was ≈79 (i.e., total DD accumulated from egg to peak trap capture divided by the mean daily DD accumulation). Given that oviposition of the summer generation occurs usually by 15 June, if the same DD of 1018 is assumed to be required to complete development from egg to peak (potential third), then a third peak will be expected to occur approxi-

Table 5. Validation of the polynomial and Weibull models in two unmanaged peach orchards in Clanton, AL, in 2009 and 2010

Model	Trap capture	Predicted degree-day (2000–2008)	2009 (First orchard)		2010 (First orchard)		2009 (Second orchard)	
			Obser.	Obser.-pred.	Obser.	Obser.-pred.	Obser.	Obser.-pred.
Polynomial	First (spring)	99.2	183.9	84.7	96.4	**−2.8**	226.4	127.2
	First (spring) peak	245.8	226.4	**−19.4**	163.7	−82.1	265.6	**19.8**
	Second (summer) peak	1,105.4	1133.8	**28.4**	930.4	−175	707.6	−397.8
	Third (potential) peak[a]	1,758.2			1315.4	−442.8	1716.1	**−42.1**
				R = 0.623*		R = 0.491NS		R = 0.343 NS
Weibull	First (spring)	109	183.9	74.9	96.4	**−12.6**	226.4	117.4
	25%	168						
	First (spring) peak	220	226.4	**6.4**	163.7	**−56.4**	552.1	332.1
	50%	252						
	75%	396						
	95%	731						
				R = 0.604*		R = 0.698*		$R = \infty$

Bold indicates degree-days for which the observed cumulated degree-day differ from the mean predicted degree-day (2000–2008); Differences less than or equal to 56 DD are judged to be acceptable predictions; Negative value indicates observed degree-day occurred before the predicted; R is correlation coefficient of observed vs predicted cumulative degree-day; NS represent not significant at $P = 0.05$.

* Significant at $P = 0.01$.

[a] Represents potential third peak.

mately 1 September. However, because the mean daily DD accumulation from June to August is always greater than that observed during spring, the number of days for which the DD of 1018 required for the insect to complete development from egg to peak trap capture will be reduced and hence expected to occur by the end of July. Occurrence of a late summer (third) generation of plum curculio is especially likely in late season peach varieties such as 'Flameprince' and 'Autumnprince', which will provide food and oviposition resources for the adults. This result supports previous studies which reported that plum curculio is bivoltine (or potentially multivoltine) in peaches and plums in Georgia (Snapp 1940, Horton and Ellis 1989) and some other parts of the southeastern United States (Johnson et al. 2002b). Ongoing studies on population dynamics of the plum curculio in peaches will likely confirm occurrence of this third generation.

Comparing the two models, the polynomial model predicted the DDs at first (spring generation) and peak trap captures to occur at 99 and 245 (biofix of 1 January at LTT 10°C), respectively, whereas the predicted cumulative DD for first and peak trap captures by using the Weibull model were 108 and 220 (biofix of 1 January at LTT 10°C), respectively. The difference of the cumulative DD between the two models for first and peak trap captures were nine and 25, respectively. Because the mean DD accumulation per day was ≈8 during the spring migration, the first trap capture was predicted a day apart, whereas the peak trap capture was predicted 3 d apart by the two models. However, the validation tests showed less accuracy of both models in general. This may be due to variable weather conditions that could occur from year to year in Alabama. For example, an intense freeze event early in the season in 2007 coupled with drought conditions resulted in the loss of many fruits, which may have contributed to the low accuracy of the model in predicting the first and peak trap capture of the spring generation. The variations in the observed time of first and peak trap captures suggest that trap capture and DD are not the only factors that could determine the seasonal occurrence of plum curculio.

In conclusion, our results showed that the first and peak trap captures of the spring generation of plum curculio in central Alabama can be predicted using DDs accumulated from regional climate data records. Validation of the models showed that DDs reliably predicted the peak trap capture (two out of three scenarios) but not the first trap capture (one out of three scenarios). Thus, DDs may not always effectively predict plum curculio events in nature, as cautioned by various studies (Andrewartha and Birch 1954, Wagner et al. 1984, Higley et al. 1986). Our inability to obtain high-resolution (hourly) temperature data for the calculation of the DDs could have contributed to the low accuracy of the models, as reported for some other insects (Raworth 1994, Brewer and Hoff 2002). In addition, plum curculio initial colonization into orchards is not only dependent on temperature but also on host plant volatiles and precipitation. Studies are ongoing to determine some of the possible confounding factors that may influence the performance of the models. Although the models were intended to be used as a guide in timing the insecticide applications against plum curculio, the results suggest that additional validation data may be required before they can be recommended for grower adoption. It is hoped that, as more data are available, the models can be used to apply any insecticides with relatively long residual activity (10–14 d or more) to manage plum curculio.

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