

Cross-correlation patterns of air and soil temperatures, rainfall and *Diaprepes abbreviatus* root weevil in citrus

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Abstract: Time series cross-correlation analysis is appropriate when measuring relationships between two different time series. Using this approach, the authors quantified the relationship between the time series air temperature (AT), soil temperature (ST), rainfall, relative humidity (RH) and *Diaprepes abbreviatus* (L.) (Coleoptera: Curculionidae) root weevil across a period of 30 months, and examined how closely the distribution of *Diaprepes* root weevil was related to AT, ST, rainfall and RH within this period of time. The study was conducted on a poorly drained Spodosol in a citrus [*Citrus sinensis* (L.) Osb.] grove in DeSoto County, south-west Florida, from April 2001 to September 2003. Adult weevil populations were monitored using 100 Tedders traps in a 30 × 15 m grid. Weather data (0.6 m AT, 0.1 m ST, 2 m rainfall and 2 m RH) were monitored by Florida Automated Weather Networks. The monthly mean and standard deviation were 22.3 ± 4.0 °C for AT, 24.7 ± 4.2 °C for ST, 146.0 ± 122.7 mm for rainfall, 78.2 ± 4.7% for RH and 0.74 ± 0.59 adults trap⁻¹ for the root weevil. Weevil density was positively correlated with AT ($r = 0.45$, $P < 0.0133$), ST ($r = 0.49$, $P < 0.0067$) and rainfall ($r = 0.38$, $P < 0.0450$). The environmental variables AT, ST, rainfall and RH were correlated with each other ($0.42 < r < 0.99$, $0.0246 < P < 0.0001$). All weather and *Diaprepes* variables were autocorrelated with each other within a time of 3 months. The cross-correlation coefficients varied between -0.59 and 0.65 for the pair-variable between *Diaprepes*, AT, ST and rainfall, and these pair-variables were correlated across a time period of 4 months. The present results suggested that warm, wet conditions contributed to the root weevil outbreaks, and environmental temperature and rainfall were the variables most closely related to *Diaprepes* root weevil distribution in time.

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Keywords: citrus root weevil control; Coleoptera: Curculionidae; insect–environment relations; regression model; time series analysis

1 INTRODUCTION

The root weevil, *Diaprepes abbreviatus* (L.) (Coleoptera: Curculionidae), native to the Caribbean, has become a major pest of citrus and other crops in Florida.^{1–3} Florida citrus are grown on shallow and poorly drained ‘flatwoods’ areas, which have waterlogged soil problems owing to high rainfall and low elevation. Soil waterlogging and *Diaprepes* root weevil infestations can occur simultaneously in citrus groves,⁴ and studies conducted in Florida citrus ecosystems have found that soil waterlogging could damage citrus tree roots and reduce *Diaprepes* larval survival because of soil compaction and lack of gas exchange.⁵ *Diaprepes* adult weevils moved only 0–72 m in a period of over 10 weeks in the summer in citrus groves,¹ and their abundance in citrus groves was likely related to seasonal weather² and associated with certain physical and chemical soil characteristics.^{4,6} It was also reported that ambient temperature influenced *Diaprepes* larval growth, pupation and emergence.⁷

Climate and weather can substantially influence the occurrence, timing, development, dispersal and

movement of insects.^{8–15} Many studies have suggested that temperature is one of the most important factors affecting biological processes in all living organisms.^{9–18} Anthropogenically induced climatic change arising from increasing levels of atmospheric greenhouse gases would be likely to have a significant effect on agricultural insect pests.⁹ Plant canopy temperature was related to ambient temperature, and greenbug and leaf aphid outbreaks occurred with high summer temperature in Texas.¹⁰ Air temperature change has also caused outbreaks of bark beetles in Texas,¹³ and linked to the developmental time of an Asian leaf beetle for the biological control of a pest shrub, Saltcedar, in California.¹⁸ However, the relationships between insect abundance and soil temperatures are not as well known.

Seasonal precipitation is also an important factor for insect survival,^{14–15,19} and soil moisture and nutrient status influence cycles of insect pest and most soil fauna.^{10,20–22} Correlations between soil water status and insect population dynamics have been established in many ecosystems.^{10,14–15,20–23} The survival and

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spread of insects and pathogens were directly linked to precipitation,¹⁴ and movement, survival and vertical distribution of the subterranean burrower bug, *Cyrtomenus bergi* Froeschner, was dependent on soil moisture.¹⁹ Also, insect larval mortality was generally low in low-moisture soil, and entomopathogenic nematodes needed high relative humidity to survive.²⁰ In citrus root weevils, population peaks of *Diaprepes* adult population appeared following high rainfall in the spring.²

Insect pest abundance, insect behavior, solar radiation, natural illuminants, plant canopy temperatures and other plant and soil characteristics are often variable in space and time.^{10,24–30} Knowledge of spatial dynamics and the underlying mechanism for insects may lead to a systems approach to pest management,²⁵ and plant, soil and insect management strategies have been established using time series analysis or multivariate linear stepwise regression.^{6,10,26–30} The cross-correlation functions (CCF) between two variables have been used to quantify the fluctuation structures of insect, animal, soil water or canopy temperature variations with time.^{10,26–30} The long-term dynamics and synchrony of insect and animal populations have been quantitatively described in autocorrelation and cross-correlation plots to show their associations in different habitats.^{23,30}

Air temperature and rainfall are among the most important environmental factors in citrus production systems, as shown by the influence of temperature and solar radiation in the apple orchard system.¹² Also, soil moisture and insect population are among the most dynamic variables in horticultural production systems.^{4,6} Since most life stages of the *Diaprepes* root weevil, including larvae and pupae, occur in soil,^{2–3} it would be useful to quantify the temporal correlations of a multiyear *Diaprepes* population with these environmental variables. The present objectives were to examine the temporal associations of *Diaprepes* root weevil variability with air temperature (AT), soil temperature (ST), rainfall and relative humidity (RH) in a citrus production system across a period of 3 years. We attempted to determine how closely these environmental variables related to the distribution of *Diaprepes* root weevils in space and time.

2 MATERIALS AND METHODS

2.1 Study sites

The study was conducted in a commercial citrus [*Citrus sinensis* (L.) Osb.] grove in DeSoto County (27°06'55"N, 81°55'05"W), south-west Florida. The grove consisted of flatwoods 'Hamlin' orange trees on sour orange/bittersweet rootstocks (*Citrus aurantium* L.), planted in 1990. The soil was classified as Sandy, Siliceous, Hyperthermic Typic Haplaquods Spodosol,³¹ formed in wide beds of sandy marine sediment on the Suwannee Limestone. This sandy soil possessed low water holding capacity, and was poorly drained owing to its low elevation.

The trees at the grove were in four-row beds with 3 × 8 m tree spacing and have been infested by *Diaprepes* root weevils since 1997, 4 years prior to the beginning of the study. During the study period, the orange trees received regular grove care including irrigation, fertilization and pest control. The pest treatment included four uniform sprays of carbaryl (Sevin 80 S; Bayer Crop Science, Research Triangle Park, NC) at a rate of 2.8 kg ha⁻¹ each application. Fruit yields at the grove varied between 36 and 50 Mg ha⁻¹ per year.

2.2 Adult weevil monitoring and weather data

The *Diaprepes* adult populations were monitored weekly using modified pyramidal Tedders traps, the typical traps used in citrus root weevil monitoring in Florida.² A total of 100 Tedders traps were used to monitor the adult weevil population across the study area. The traps were placed near the tree canopy halfway between the tree trunk and the drip line, 15 m apart, in the two central rows on each four-row tree bed. The 100 traps formed a 30 × 15 m grid in an area of 260 × 180 m. The captured weevils were counted weekly for a continuous period of 30 months, from April 2001 to September 2003.

The weather data for the site were obtained from the Florida Automated Weather Network (FAWN), University of Florida. The data were taken hourly on a basis of 24 h per day at the FAWN weather station closest to the grove, about 2 km away. Air temperature (AT) was detected using a CS107 sensor thermistor (Campbell Scientific Inc., Logan, UT), installed at 0.6 m above the soil surface. Soil temperature (ST) was also detected using a CS107 sensor, installed at 0.1 m depth in the soil. Rainfall was measured using a TE525-L rain gauge (Texas Electronics Inc., Dallas, TX), installed at 2 m above the soil surface. Relative humidity (RH) was detected using a HMP45 sensor (Campbell Scientific Inc., Logan, UT), installed at 2 m above the soil surface (<http://fawn.ifas.ufl.edu/tour/towerinfo.asp>).

2.3 Autocorrelation and cross-correlation analysis of data

Descriptive statistics, correlation and regression analyses for insect and environmental weather data were done using PROC UNIVARIATE, PROC CORR, PROC GLM and PROC NLIN.³² Homogeneity of variance of datasets was verified using the Bartlett test, and normality and residual distribution of data sets were confirmed using PROC UNIVARIATE.³²

Spatial interdependence for the *Diaprepes*, AT, ST, rainfall and RH was quantified with a correlogram $\rho(h)$, as shown by Li *et al.*^{26,27} The autocorrelation function is the ratio of sample covariance function $C(h)$ and measurement variance σ^2 . The sample covariance function $C(h)$ and autocorrelation function $\rho(h)$ were calculated as follows:

$$C(h) = \frac{1}{n(h) - 1} \sum_{i=1}^{n(h)} [z(x_i) - \bar{z}][z(x_i + h) - \bar{z}] \quad (1)$$

$$\rho(h) = \frac{C(h)}{\sigma^2} \tag{2}$$

where $n(h)$ in Eqn (1) is the number of pairs of sample variables at time h apart, $z(x)$ is the variable value at time x , $z(x + h)$ is the variable value at time $x + h$, h is the lag between measurements, \bar{x} is the mean of all measurements and x and h are vectors.^{26,27}

The cross-correlation function $\gamma_{xy}(h)$, a statistical measure timing the movement and proximity of alignment between two different information sets of time series, was determined with the cross-covariance function $C_{xy}(h)$, described in Li *et al.*^{27,28} as follows:

$$C_{xy}(h) = \frac{1}{n(h)} \sum_{i=1}^{n(h)} (x_{i+h} - \bar{x})(y_i - \bar{y}) \tag{3}$$

$$\gamma_{xy}(h) = \frac{C_{xy}(h)}{\sigma_x \sigma_y} \tag{4}$$

where, in Eqn (3), $n(h)$ is the number of pairs of sample points at time h apart, x_{i+h} is the measurement of x at time $i + h$, y_i is the measurement of y at time i , h is the time between measurements, \bar{x} and \bar{y} are the mean for x and y respectively and i and h are vectors.^{27,28} In Eqn (4), σ_x and σ_y are the standard deviations of x and y respectively.

The ranges of the autocorrelation and cross-correlation functions are from -1 to 1 . The closer the autocorrelation value is to 1 (or -1), the more closely the two values of the same variable at times x_i and x_{i+h} are correlated.²⁶⁻²⁹ Similarly, the closer the cross-correlation value is to 1 (or -1), the more closely the information of the two datasets is related.²⁶⁻²⁹ The cross-correlation coefficient $\gamma_{xy}(h)$ for adult weevil (y), AT, ST, rainfall and RH (x) were estimated using the SAS integrated moving average (ARIMA) procedure, the PROC ARIMA.³³ A 95% confidence threshold was applied for determining the significant cross-correlation time lag.²⁷⁻²⁹

Table 1. Descriptive statistics of *Diaprepes* root weevil monthly density, 0.6 m air temperature (AT), 0.1 m soil temperature (ST), 2 m rainfall and 2 m relative humidity (RH). Data were monitored during period from April 2001 to September 2003 ($n = 30$ months)

Variable ^a	AT (°C)	ST (°C)	Rainfall (mm)	RH (%)	<i>Diaprepes</i> (adults trap ⁻¹)
Mean	22.3	24.7	146.0	78.2	0.74
SD	4.0	4.2	122.7	4.7	0.59
CV	0.18	0.17	0.84	0.06	0.80
Maximum	26.5	29.0	406.7	85	3.07
Minimum	12.1	14.6	2.3	67	0.15
Kurtosis	-0.2	-0.4	-0.8	0.2	7.5
Skewness	-0.9	-0.9	0.6	-0.9	2.3

^a SD, standard deviation; CV, coefficient of variation.

3 RESULTS

3.1 Temporal patterns of air and soil

temperatures, rainfall and *Diaprepes* root weevil

During the study period (April 2001–September 2003), the monthly AT (0.6 m) was 22.3 ± 4.0 °C [mean and standard deviation (SD)], and the monthly ST (0.1 m) averaged 2.4 °C higher than the AT (Table 1). The monthly total rainfall was high (146.0 mm) and variable (SD = 122.7 mm). Relative humidity was high (78.2%) with little variation (SD = 4.7%). *Diaprepes* monthly density was highly variable (0.74 ± 0.59 adults trap⁻¹) (Table 1). Among the variables, monthly rainfall and *Diaprepes* density had the highest coefficient of variation (Table 1). The temporal distribution of the *Diaprepes* population was skewed, i.e. kurtosis 7.5 (Table 1), a value greater than the skewness threshold (kurtosis 3).

Temporal patterns of monthly mean AT and ST showed a similar S-curve across the 3 years, with maximum AT and ST occurring in July or August each year (Fig. 1A). Soil temperature was evenly higher than AT across the 30 months, except for the winter of 2003 where both temperatures were equal. The lowest AT (12.1 °C) and the lowest ST (14.6 °C) in the 3 year period occurred in December 2002 (Fig. 1A). The *Diaprepes* density consistently increased with AT and ST from the spring to the summer, then declined with decrease in AT and ST from the fall to the winter in the 3 year period (Fig. 1). The difference in *Diaprepes* density over the 3 years was significant (ANOVA, $F = 9.85$, $df = 2$, 297, $P < 0.0001$). The most variable *Diaprepes* population in the 3 year period was in 2001, where the maximum monthly density was 3.07 weevils trap⁻¹ in July compared with 0.15 weevils trap⁻¹, the minimum monthly density in November (Fig. 1B).

Total weekly rainfall generally occurred during the summer across the 3 years (Figs 2A, B and C), and there was no rain in the relatively cool fall of 2001 and in the winter of 2003 (Fig. 2B). The monthly total rainfall maximum (406.7 mm) occurred in September 2001, and the monthly minimum (2.3 mm) occurred in November 2001, the same timing as the minimum monthly density in the 3 year period (Fig. 1B). The *Diaprepes* weekly density generally coincided with high rainfall during May and September each year, except for 2003 (Figs 2D, E and F). *Diaprepes* weekly density varied between 0.23 ± 0.34 adults trap⁻¹ in 2001, 0.16 ± 0.13 adults trap⁻¹ in 2002, and 0.14 ± 0.09 adults trap⁻¹ in 2003. Timing of rainfall and *Diaprepes* weekly peaks was not even (Fig. 2).

3.2 Linear correlation, autocorrelation and cross-correlation between weather variables and *Diaprepes* root weevil

Diaprepes density was positively correlated with AT ($P < 0.0133$), ST ($P < 0.0067$) and rainfall ($P < 0.045$) (Table 2). Correlations between AT, ST and rainfall were highly significant ($0.53 < r < 0.99$, $P < 0.0034$). Relative humidity was correlated with AT

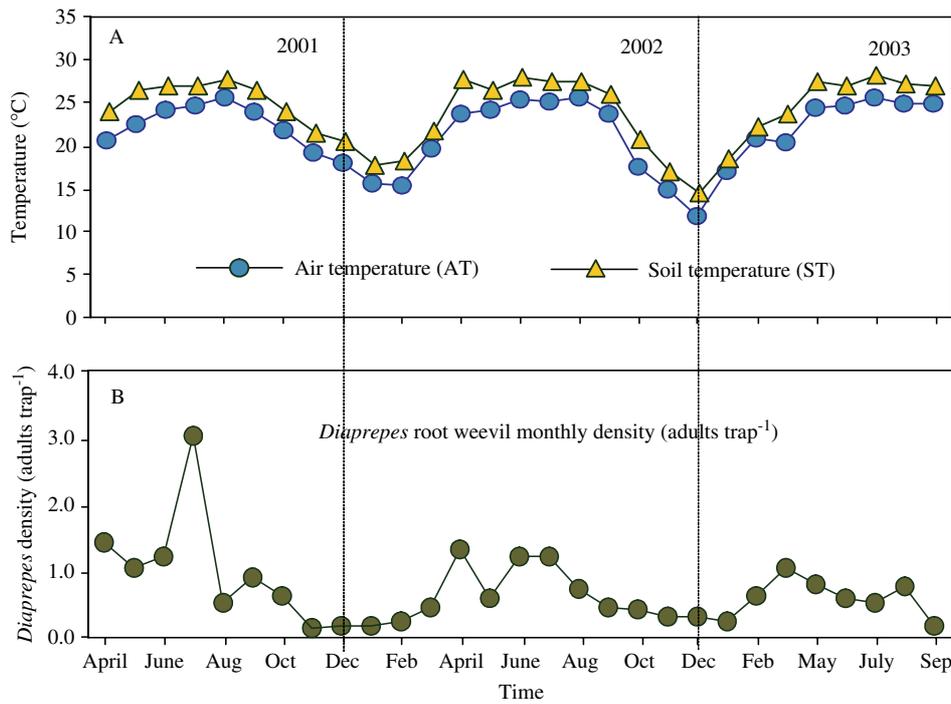


Figure 1. Temporal patterns of (A) monthly 0.6 m air temperature (AT, °C) and 0.1 m soil temperature (ST, °C) and (B) *Diaprepes* root weevil monthly density (adults trap⁻¹) across April 2001 to September 2003. Each point represents the mean of $n = 24 \text{ h} \times 30 \text{ days}$ for AT and ST and $n = 4 \text{ weeks} \times 100 \text{ traps}$ for *Diaprepes* density.

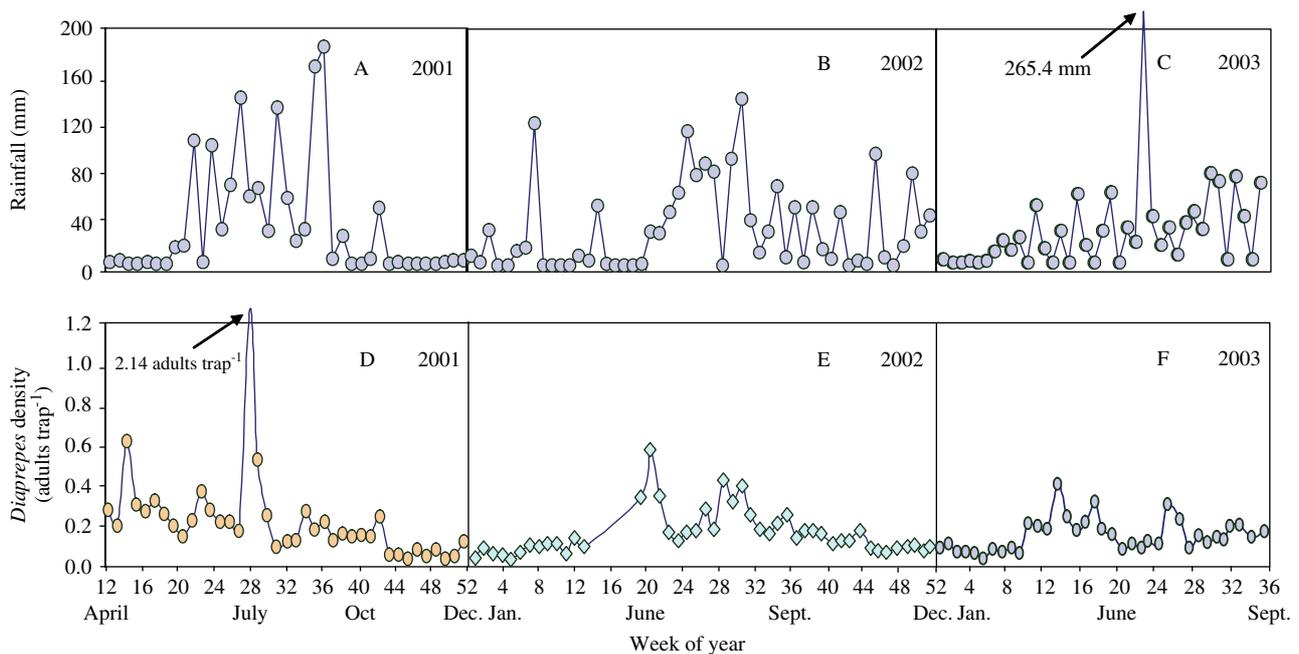


Figure 2. Temporal patterns of (A, B, C) total weekly 2 m rainfall (mm) and (E, F, G) *Diaprepes* root weevil weekly density (adults trap⁻¹) across April 2001 to September 2003. The *Diaprepes* weekly density was the mean of $n = 100$ traps.

($P < 0.0246$) and rainfall ($P < 0.0001$) (Table 2). Soil temperature was highly related to AT ($R^2 = 0.95$), and the weekly ST was closer to the regression line when the weekly AT values were equal to or greater than 23 °C (Fig. 3A). As plotted against AT and ST, the best-fit model for describing *Diaprepes* density patterns across the time of 120 weeks was exponential (Figs 3B and C). Except for two high weekly densities, all high weekly *Diaprepes* densities (>0.25 weevils trap⁻¹)

occurred with high AT values between 20 and 26 °C (Fig. 3B) and with a high ST value ranging from 22 to 29 °C (Fig. 3C).

Autocorrelation functions $\rho(h)$ (ACF coefficients), the correlations between two values of the same variable at times x_i and x_{i+h} , for *Diaprepes*, AT, ST, rainfall and RH showed the results of cyclical effects (Fig. 4). As the time lag number increased, the ACF coefficients became alternately positive and

Table 2. Pearson correlation coefficients (*r*) between the *Diaprepes* root weevil monthly density, 0.6 m air temperature (AT), 0.1 m soil temperature (ST), 2 m rainfall and 2 m relative humidity (RH)

	<i>Diaprepes</i> (adults trap ⁻¹)	AT (°C)	ST (°C)	Rainfall (mm)	RH (%)
Pearson coefficient <i>r</i>					
<i>Diaprepes</i>	1				
AT	0.45	1			
<i>P</i>	0.0133				
ST	0.49	0.99	1		
<i>P</i>	0.0067	<0.0001			
Rainfall	0.38	0.56	0.53	1	
<i>P</i>	0.0450	0.0051	0.0034		
RH	0.00	0.42	0.31	0.68	1
<i>P</i>	0.9970	0.0246	0.1000	<0.0001	

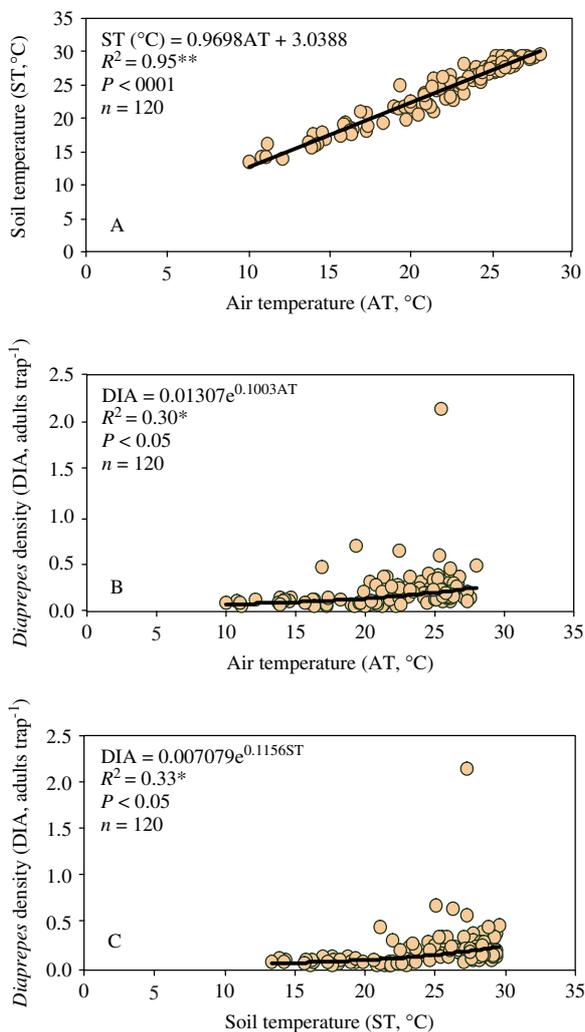


Figure 3. (A) Linear regression relationship of soil temperature (ST, °C) vs air temperature (AT, °C). (B) Exponential regression relationship of *Diaprepes* root weevil weekly density (DIA, adults trap⁻¹) vs air temperature (AT, °C). (C) Exponential regression relationship of *Diaprepes* root weevil weekly density (DIA, adults trap⁻¹) vs soil temperature (ST, °C).

negative and approached zero at time lag 3 for all the *Diaprepes*, AT, ST and rainfall variables (Fig. 4). The ACF coefficient ranges were greater for the AT

(Fig. 4B) and ST (Fig. 4C), with more significantly different values (points above the dashed lines) than for *Diaprepes* (Fig. 4A) and rainfall (Fig. 4D). The RH had low and constant ACF coefficients (points below the dashed lines in Fig. 4E). Each variable was autocorrelated within three time lags (months), based on the time lag at their zero ACF coefficients (Fig. 4).

The cross-covariance functions $C_{xy}(h)$ varied between -134.6 and 128.3 for *Diaprepes* (*y*) vs AT (*x*), -142.1 and 133.1 for *Diaprepes* (*x*) vs ST (*y*) and -3081.4 and 3776.8 for *Diaprepes* (*y*) vs rainfall (*x*). The cross-correlation functions $\gamma_{xy}(h)$ (CCF coefficients) ranged between -0.58 and 0.55 for *Diaprepes* vs AT, -0.59 and 0.65 for *Diaprepes* vs ST and -0.44 and 0.54 for *Diaprepes* vs rainfall. The CCF coefficients showed a cyclic, positive feedback relationship between *Diaprepes* and AT (Fig. 5A), *Diaprepes* and ST

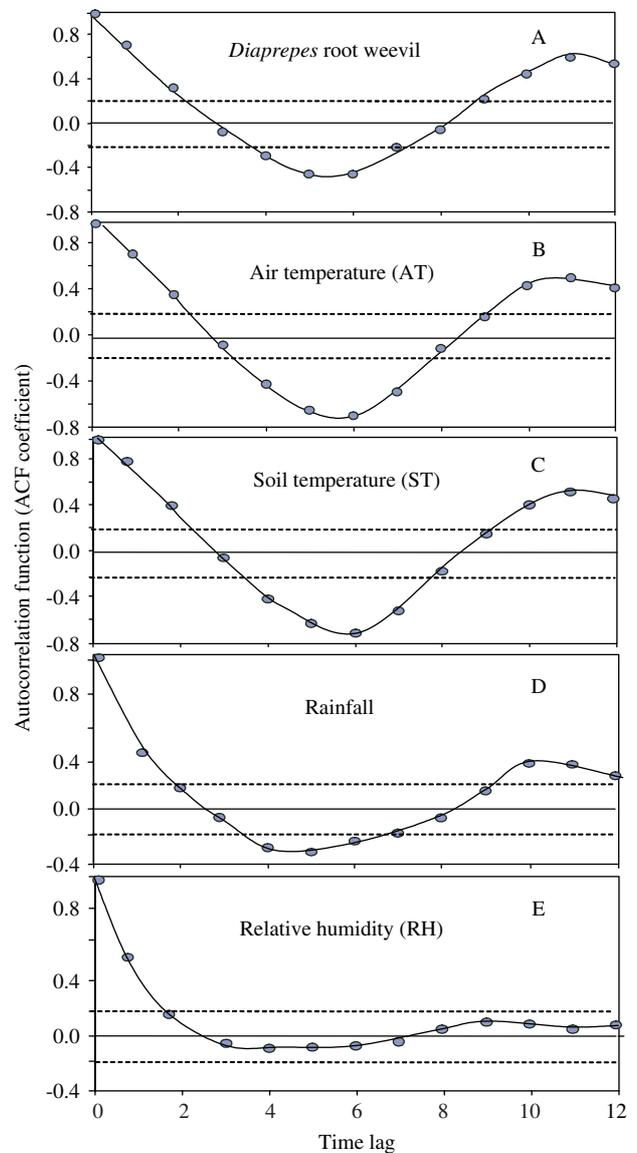


Figure 4. Autocorrelation functions (ACF coefficients) for (A) *Diaprepes* root weevil, (B) air temperature (AT), (C) soil temperature (ST), (D) rainfall and (E) relative humidity (RH). The dashed lines represent significant levels; any coefficient above the dashed line is significantly different from 0 at *P* < 0.05 probability.

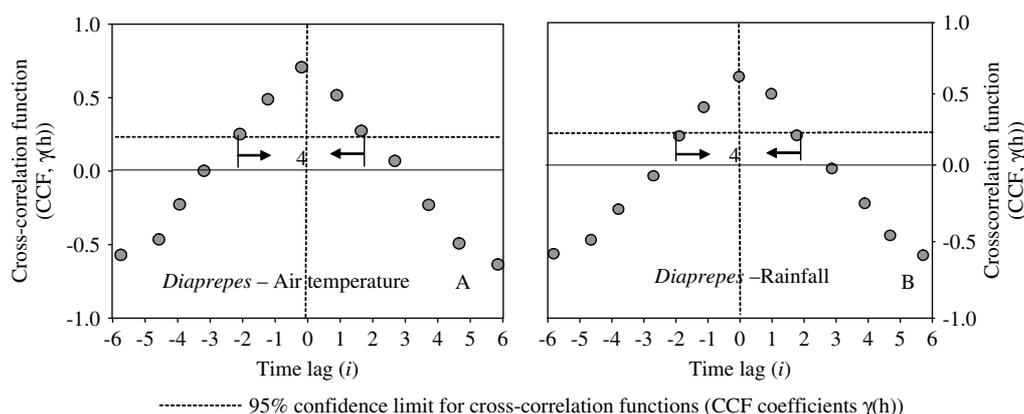


Figure 5. Cross-correlation functions (CCF coefficients) for (A) *Diaprepes* root weevil vs air temperature and (B) *Diaprepes* weevil vs rainfall. The dashed lines represent the 95% confidence limit for the cross-correlation functions.

(data not shown) and *Diaprepes* and rainfall (Fig. 5B). By accounting for the 95% confidence threshold as described previously,^{28–29} the weevil, AT and rainfall were temporally related across four time lags (months) (Fig. 5). The CCF coefficients for *Diaprepes* vs RH were near zero (graph not shown).

4 DISCUSSION

4.1 Impact of changes in air and soil temperatures and rainfall on *Diaprepes* development

The positive correlations between *Diaprepes* weevils, AT, ST and rainfall variables over a period of 30 months (Table 2) suggested that the weevil population would increase with increasing air/soil temperatures and rainfall. These multiyear positive correlations also suggested that the weevil density at the grove would be influenced not only by characteristics of the soils in which their host trees were growing^{4,6} but also by temporal patterns of ambient temperature and rainfall. In this citrus grove, the *Diaprepes* weevil density was correlated with sand content, soil pH and Mg and Ca concentrations at $P < 0.0282$.⁶ Based on the Pearson r correlation coefficients and the P values (Table 2), the degree of influence of air and soil temperatures and rainfall on the temporal distribution of *Diaprepes* adult weevils was greater than that of various soil characteristics on the weevils, as shown by Li *et al.*⁶ As influenced by many weather, soil and water factors, the *Diaprepes* weevil distribution was skewed (kurtosis > 3) (Table 1).

The linear increase (positive correlation coefficient) (Table 2) of *Diaprepes* densities with increases in air/soil temperature supported the idea that increases in temperature had a number of implications for temperature-dependent insect pests.^{8–18} Insect larvae, adults and nematodes need adequately warm temperatures for survival and growth.^{8–18,20} *Diaprepes* larval growth was consistently fast at ambient temperatures of 22–26 °C.⁷ Nematode-inoculated soils that were originally held at cooler temperatures had greater insect mortality than those held at warmer

temperatures,²⁰ and warm daily temperatures affecting insect density were 26–37 °C.¹⁷ The present results showed that the threshold temperatures for *Diaprepes* outbreaks ranged from 20 to 27 °C weekly mean AT and from 22 to 29 °C weekly mean ST, based on the regression equations (Fig. 3B and C). In citrus groves, *Diaprepes* adults moved little, with 81% (118/146) of marked adults moving within 0–72 m over a time of 10 weeks.¹ It would be useful to examine whether there is any influence of weekly temperature or rainfall on weevil movement.

The potential explanations about mechanisms for weather conditions affecting insect development and patterns and for high temperature promoting insect outbreaks are numerous. High temperature would prevent the development of the fungal pathogens that infect and kill insects.⁸ When ambient temperature, solar radiation and relative humidity were high, these insect species were able to increase their body temperatures, which induced changes in behavior.^{12,17,18} Plant-eating insect outbreaks in the spring would occur because of better food sources and higher nutritional quality in plant tissues.⁸ Amino acids (praline), nitrate, betaine and sugars would accumulate to higher than normal levels in plant tissues under warm temperature.^{8,10,11,13} Other explanations for mechanisms are that high temperature would stress plants and influence host plant metabolic rate, leaf temperature and rate of water loss to affect growth, maturation and habitat selection of insects^{10,13,17,18} Also, some insects have heat and infrared receptors, making host plants with high temperature or more reflectance-transmission properties more attractive to these insects.^{8,10,24}

Insects respond to diverse environmental signals, and a combination of biotic and abiotic factors will alter their responses not only to ambient temperature but also to precipitation.^{18,21} In addition to the warm temperature, high precipitation reinforced the *Diaprepes* outbreaks in the spring across the 30 months (Fig. 2), which was in line with the results reported in several studies^{10,19–21} Rainfall had direct effects on insect life cycles by influencing nutritional

quality in plant tissues, and rainfall was one of the predictive indices of spring outbreaks of insects.²² With the abundant rain (1752 mm year⁻¹) in the citrus production areas of Florida, flooding and soil water saturation have contributed to citrus tree water stress and root injury.^{4,6}

The lack of correlation between relative humidity and the *Diaprepes* population (Table 2) would be explained by the low variability of the ratio of the amount of water vapor in air to the saturation vapor concentration. This RH parameter was constant across the 30 months (Table 1) so did not result in any influence on the weevil distribution. In an apple orchard, all weather factors (ambient temperature, solar radiation and wind speed), except relative humidity, affected significantly the foraging activity of pollinator insects.¹² However, *B. bassiana* fungal species were more efficient in infecting the host insect pests under high humidity (97.5%) than at low humidity levels (75–80%).²⁰

4.2 Implication of the weather variables in citrus root weevil control

The weather conditions shown in this study (Figs. 1 and 2) are representative of typical citrus growth conditions, similar to the weather patterns in Leesburg in Florida.⁷ The implication of the present results for management practices would be the use of the autocorrelation and cross-correlation time lag ranges to determine optimum timing of insecticide applications for weevil control with regard to ambient temperature and rainfall patterns. The 3 month autocorrelation time range for the weather and *Diaprepes* variables (Fig. 4) suggested that the patterns of these variables were seasonal. Although their autocorrelation functions at time lag 3 were not significantly different from zero (within the dashed line limits), these functions at time lag 3 were still autocorrelated with their functions at time lag 2, based on their autocorrelation structure. For a 21 year dataset, the fluctuations of six species of rodent populations were autocorrelated within three time lags.³⁰ A single generation from *Diaprepes* oviposition to adult emergence was estimated to be 22 weeks at 26 °C in the laboratory.⁷ It would be useful to quantify the autocorrelation time range within *Diaprepes* life stages with adapting field temperature and precipitation conditions from the present results.

The similar values of the cross-correlation functions for *Diaprepes*, AT, ST and rainfall (Fig. 5) revealed that temperature and rainfall were two variables closely related to the timing of *Diaprepes* weevil movement. However, the temporal correlations between the root weevil, temperature and rainfall were limited to a time frame of four lags (or 4 months). In other studies, the long-term (21 year) fluctuations of six species of animal populations were cross-correlated with ambient temperature or precipitation within 4–8 time lags.³⁰ The present cross-correlation analysis gained the correlation degree between two time series

variables for pest management purposes with regards to environmental temperature change and rainfall frequency. The results suggest that optimum timing of insecticide applications for *Diaprepes* root weevil would be in April, when it is the time lag for the weevil outbreak with warm temperature and high rainfall.

The primary tool for managing *Diaprepes* is application of insecticides.^{4,6} The present results would also indicate that the more abundant weevil population that occurred during the high rainfall period (Fig. 2) could pose a problem for chemical applications for weevil control in the spring or in the fall. Citrus trees, root weevil and insecticides are exposed to a broad range of temperatures. The implication of the present results would also be the need to examine further the effects of temperature, rainfall, light and radiation on the efficacy of various insecticides in controlling *Diaprepes* root weevil under field conditions.

The present results suggest the need to investigate further the influence of ambient temperature and rainfall on entomopathogenic nematode survival and persistence. In Florida, entomopathogenic nematodes have also been adapted to infect *Diaprepes* larvae living in soil.³ Entomopathogenic nematodes have the potential to be important biological control agents for *Diaprepes* larvae.³ The present results also support the use of meteorological data for model development to predict insect seasonal emergence, density and survival. Modeling has long been recognized as a key tool to help solve pest problems.^{18,22} A linear relationship between insect developmental rate and temperature was presumed in degree-day models within the range of ecologically relevant temperature variations.²²

Although the role and importance of ambient temperature and rainfall in *Diaprepes* root weevil development patterns found in this study were in line with the insect and climate relations reported in many other studies, more monitoring is still required to confirm if these correlations apply in different climatic conditions. The potential impacts of climate change on insects are very complex,^{9,13,14} but the present results suggest that further environmental studies on *Diaprepes* root weevils of citrus should be pursued to determine how the survival and development of this species might be affected by potential future increases in temperature.

5 CONCLUSIONS

Environmental factors of air/soil temperature and rainfall had a positive correlation with *Diaprepes* root weevil development in the citrus production system. Relatively warm, wet conditions promoted citrus adult root weevil outbreaks. Air and soil temperatures were the most dominant variables on *Diaprepes* root weevil density. The threshold weekly temperatures for the root weevil outbreak were 20–27 °C mean air temperature and 22–29 °C

mean soil temperature. The weevil, AT, ST, rainfall and RH variables were autocorrelated with each other within a 3 month time lag. The weevil, AT, ST and rainfall pair-variables were cross-correlated within a 4 month time lag. Air/soil temperature and rainfall were the variables closely related to the timing of *Diaprepes* adult weevil development. The implications and benefits of the present results are the use of autocorrelation and cross-correlation ranges for determining optimum timing of insecticide applications, and the consideration of the effect of possible climatic changes in pest management research. It is suggested that increases in temperature or precipitation have a number of implications in development of meteorology-dependent insect pests in space and time.

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