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Time series forecast and soil characteristics-based simple and multivariate linear models for management of *Diaprepes abbreviatus* root weevil in citrus

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Abstract

Synthesis of insect and soil variable patterns in space and time via process models would be useful for reducing the cost of field monitoring and for achieving improved integrated pest management. During 2001–2003, we monitored the *Diaprepes abbreviatus* (L.) root weevil population in a flatwoods citrus grove containing a sandy Alfisol and a loamy Mollisol in Hendry County, South Florida. Our objectives were to examine the multi-year correlations of the *Diaprepes* root weevil with soil characteristics, and to develop a time series model and soil variable-based simple and multivariate linear models for predicting weevil patterns in space and time. Adult weevils were monitored weekly using 100 Tedders traps arranged in a $30 \times 12\,\mathrm{m}$ grid. Gravimetric soil water content (SWC), time-domain-reflectory (TDR) volumetric SWC, soil organic matter content (SOM), clay, sand, silt, pH, and Mehlich-I extractable P, K, Ca, Mg, Fe and Mn concentrations were determined for each trap location. Adult weevil density was 0.023 ± 0.018 weevils m^{-2} across the 3 years, and the weevil population grew exponentially ($R^2 = 0.81$). Each year, the weevil was positively related to SWC, TDR, clay, SOM, and soil Mg, Ca and K concentrations ($0.32 < r < 0.65$, $P < 0.05$). High weevil density, SWC, SOM, and P, K, Mg and Ca levels matched the Mollisol boundary. The autocorrelation ranges for the weevil and soil variables were within the soil type unit. Time series moving average forecast of *Diaprepes* weevil development was related to the 3-year mean weevil density monitored in the field ($R^2 = 0.88$). The SWC, TDR and SOM-based simple and multivariate linear models explained 45% of the variance in the weevil patterns ($P < 0.001$). Time series and soil characteristics-based simple and multivariate linear models suggest a variable rate and less frequent spray for future management of the weevil in citrus production systems.

Keywords: Citrus root weevil control; Linear model; Soil–insect relations; Time series analysis

1. Introduction

Management of root weevil pest is often obtained by repeated foliar application of chemical treatments when pest densities exceed an economical threshold that requires treatment (Graham et al., 2003; Byers and Castle, 2005). However, the excess use of costly pesticides can harm the environment (Byers and Castle, 2005). The root weevil *Diaprepes abbreviatus* (L.) is a serious pest of citrus in Florida. *Diaprepes* adult weevils are citrus leaf feeders and females deposit egg masses glued in the citrus tree canopies (Graham et al., 2003; McCoy et al., 2003). Hatching neonates fall onto the soil and their larvae are soil-inhabiting root predators (Li et al., 2004). *Diaprepes* larvae feed on citrus tree roots and grow in the soil. Growth of *Diaprepes* larvae could be an increase of 36–375 times their weight as 1-day-old neonates within 30 days of infestation on citrus roots (Li et al., 2006a), and 240–370 times within 40 days of infestation on citrus roots in the greenhouse (Li et al., 2007a). The time required for a single generation from oviposition to adult emergence is estimated to be 154

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days at 26 °C in the lab (Lapointe, 2000). Long period feeding of *Diaprepes* larvae can break the resistance of citrus roots to infection by *Phytophthora* spp., and both larval feeding and disease can lead to tree decline to an unproductive state or death by extensive larval root injury (Graham et al., 2003). Typically, citrus growers control the *Diaprepes* weevil population by four applications of insecticides each year, and usually uniform rate is applied over the orchard (Li et al., 2007b).

Soil water content (SWC) and textural class influenced plant growth in different soils (Li et al., 2002), and soil moisture and nutrients were related to soil organism cycles, leaf quality and herbivorous insect population (Klironomos et al., 1999; Lower et al., 2003). Since *Diaprepes* larvae, pupae and teneral adults are soil-habiting, soil physical and chemical characteristics could influence larval development and adult weevil density, examined in the environmental controlled greenhouse studies and in the fields at different citrus grove sites (Li et al., 2004, 2006a, 2007a, b). Among the most important factors that could influence citrus tree health status, SWC, soil texture, and Mg and Ca concentrations were associated with *Diaprepes* weevil spatial patterns (Li et al., 2004, 2007b). Air/soil temperature and rainfall were the most influential climate factors affecting *Diaprepes* adult weevil density (Li et al., 2007c). In other studies, emergence and growth of gall-insects were only slightly affected by environmental variation (Fay et al., 1996). Subsurface clay content (0.2–0.4 m) was related to moisture in the upper soil layer (0–0.2 m) in which most nematodes resided (McSorley and Frederick, 2002). Citrus trees were vulnerable to attack by the *Phytophthora*–*Diaprepes* weevil complex in fine-textured, poorly drained soils (Graham et al., 2003).

Field monitoring of insect populations for treatment determination could be critical because of the cost and labor. Costs for the citrus root weevil and the associated root disease could be as much as \$600 ha^{-1} (Graham et al., 2003). Some studies have shown a need to develop mathematical models using available field monitoring data for predicting insect patterns (Worner, 1991; Tobin et al., 2001; Crowder and Onstad, 2005; Byers and Castle, 2005). Models were useful to define problems, understand the systems, and make predictions for purposes of insect or soil management (Worner, 1991; Byers and Castle, 2005; Li et al., 2006b, 2007b). These models included time-step simulation models, non-linear degree-day models, and best-fit polynomial and exponential regression models (Tobin et al., 2001; Crowder and Onstad, 2005; Byers and Castle, 2005; Li et al., 2006b, 2007b). In an acidic Mollisol, the *Diaprepes* population in citrus grove was shown to decrease significantly with increasing soil pH and SWC, estimated using a stepwise multivariate linear model (Li et al., 2007b).

Soil units, soil boundaries, soil chemical and physical characteristics, and interpolation techniques were useful for addressing environmental concerns in production systems (Alphen Van and Stoovogel, 2000; Li et al., 2002, 2004; Fox et al., 2004). The development of these kinds of soil-characteristics tools has been the forces of the research on integrated pest management of the *Diaprepes* root weevil in Florida. New developments have included delineating management zones, mapping soil factors, and quantifying soil and *Diaprepes* weevil spatial correlation ranges (Li et al., 2004, 2005, 2007b). Citrus growers need regular soil testing to determine fertilization rates for tree management. If the temporal patterns of multi-year *Diaprepes* adult populations can be correlated to soil physical and chemical characteristics, then these soil variables could be useful for developing simple or multivariate models for weevil control purposes.

We hypothesized that if the *Diaprepes* root weevil distribution patterns were associated with time and soil variables, then mathematical equations derived from their correlations in subsequent years would be useful for predicting future *Diaprepes* weevil patterns in time and space. Our objectives were to (i) examine multi-year spatial association processes of *Diaprepes* root weevil variability with soil water, texture, SOM, pH, and macro and micronutrients and (ii) to develop a time series model and soil characteristics-based simple and multivariate linear models to estimate future *Diaprepes* adult weevil dynamics in space and time for weevil control. Mathematical models could then be combined with soil unit management zones, environmental mapping, and autocorrelation analysis for improving management of the root weevil.

2. Materials and methods

2.1. Soil and citrus trees at the study site

A 3-year study of the *Diaprepes* adult population variation with time and space was conducted in a flatwoods citrus (*Citrus sinensis* (L.) Osb.) grove in Hendry County (26°44′37″N, 81°31′33″W), South Florida, during 2001–2003. The grove consisted of ‘Hamlin’ oranger trees on Swingle citrumelo rootstocks (*Citrus paradisi* Macfad × *Poncirus trifoliata* (L.) Raf.). Across the study site, there were two soil types, Boca sand and Chobee fine sandy loam (Fig. 1), formed in thick beds of sandy and loamy marine sediments (USDA-NRCS, 2003). Boca sand zoned between Chobee fine sandy loam (Fig. 1). The Boca soil consisted of deep, poorly drained, moderately permeable soil with light sand on the surface, and a brown sandy loam subsurface overlaying limestone. The Boca sand was classified as Loamy, Siliceous, Superactive, Hyperthermic Arenic Endoaqualfs Alfisol (USDA-NRCS, 2003). The Chobee soil consisted of a deep, poorly drained, slowly permeable soil, and was a black sandy loam on the surface over a sandy clay subsurface. The Chobee loam was classified as Fine-Loamy, Siliceous, Superactive, Hyperthermic Typic Argiaquolls Mollisol (USDA-NRCS, 2003). Due to low elevation in the depression, the Boca

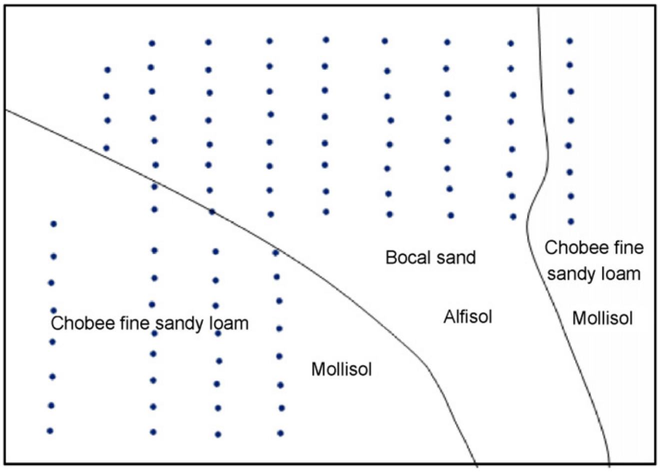

Fig. 1. Soil type boundary, soil units (Boca sand, Alfisol; Chobee fine sandy loam, Mollisol) and *Diaprepes* traps ($n = 100$) under Swingle rootstock tree canopy.

sand and Chobee loam were poorly drained and the Boca sand had a very low water holding capacity (USDA-NRCS, 2003).

The citrus trees, planted in 1992, were in two-row beds with 3 × 8 m tree spacing. A drainage furrow for evacuating surface water was necessary for every four rows of trees. The trees had been infested by *Diaprepes* root weevils during the 6 years prior to the beginning of the study. During the study period, the trees received regular grove care including irrigation, fertilization and pest control. Typically, tree irrigation was based on rain patterns, and the irrigation rate was usually 87 L tree^{-1} h^{-1} using microsprinklers. Fertilization was typically at the rates of 220 N, 44 P and 220 K kg ha^{-1} with four equal applications each year using a standard mixture of 10–2–10 (N–P–K). No lime was applied. The pest treatment involved sprays of Sevin 80S (Bayer Crop Science, Research Triangle Park, NC) with four uniform applications per year (each application per season) based on the regional recommendation. The fruit yield in the grove was between 36 and 50 Mg ha^{-1}.

Weather data at the site were obtained from Florida Automated Weather Network (FAWN, University of Florida). The 0.6-m annual air temperature (air temperature sensor installed at 0.6 m above the ground) during the study period averaged 21.9–22.1 °C, close to the 30-year average, 22.0 °C. The 0.1-m annual soil temperature (soil temperature sensor installed at 0.1 m soil depth) averaged 24.2–24.4 °C, which was 2.4 °C higher than the air temperature. The 2-m total rainfall (rain gauge installed at 2 m above the ground) varied between 1137 and 1209 mm, also close to the 30-year average, 1216 mm. Each year 30% of rainfall occurred in the spring, and 60% of the rainfall was from July to September. There was no significant difference in annual air temperature or total rainfall during the 3 years.

2.2. Adult weevil and soil assessments

The *Diaprepes* adult population was monitored weekly using 100 modified pyramidal Tedders traps as described in McCoy et al. (2003). Traps were placed near tree trunks, 12 m apart, along the tree bed in a 30 × 12 m grid pattern (Fig. 1). The weevil monitoring area was 200 × 70 m in the northern block and 100 m × 70 m in the southern block. The weevils were monitored weekly from April to December (39 weeks) in 2001, January to December (52 weeks) in 2002, and January to September (36 weeks) in 2003. Trap geo-positions were determined using a Garmin GPS12 system (Garmin International, Olathe, KS).

Soil at each trap was sampled in October 2003. A composite soil sample was taken at the 0–0.3 m depth. Soil samples were air-dried. Volumetric SWC at the 0–0.15 m depth was measured using a Scout TDR probe (Spectrum, Plainfield, IL). Gravimetric SWC was determined using soil dried at 100 °C in the oven using the method described in Li et al. (2002). The use of two methods in the SWC measurements was to test if the TDR quick measurements were reliable compared to the gravimetric SWC measurements, a time consuming method. Soil textural class was analyzed using the hydrometer method, and soil chemical characteristics were determined for pH-H_2O (m/v, 1:1), SMP-buffer pH, soil organic matter (SOM) by combustion, and the Mehlich-I extracted major and minor cations (P, K, Mg, Ca, Mn and Fe) by inductively coupled argon plasma emission spectrophotometer (Horwitz, 2000). Cation exchange capacity (CEC) was determined using the equation $\mathrm{CEC} = (\mathrm{K}/780 + \mathrm{Ca}/400 + \mathrm{Mg}/240) + \mathrm{Factor}$, where $\mathrm{Factor} = (8 - \mathrm{pH}_{\mathrm{buffer}}) \times 8$ (Horwitz, 2000).

2.3. Data analysis, mapping and forecasting

We examined the temporal and spatial variability of *Diaprepes* root weevil population and their correlations with environmental soil characteristics using their monthly mean and weekly mean data across the 3 years. Descriptive statistics and correlation were done using PROC UNIVARIATE and PROC CORR procedures (SAS Institute, 1990). Homogeneity of variance of datasets was verified using the Bartlett test, and normality and residual distribution of data sets were confirmed using PROC UNIVARIATE (SAS Institute, 1990). The ANOVA for monthly means of *Diaprepes* root weevil was done using PROC GLM. Multiple comparisons of means were done using a LSMEANS statement for a post hoc Tukey test to obtain honestly significant differences (SAS Institute, 1990). For semivariogram analysis we used PROC VARIOGRAM (SAS Institute., 1996). Soils, trees and weevils were mapped using ArcMap 9.1 (Environmental Systems Research Institute Inc, Redlands, CA).

Based on the constant and linear relationships between *Diaprepes* weevil population and soil characteristics across the 3 years, simple and multivariate linear models were determined using PROC GLM (SAS Institute, 1990) for estimating future dynamical patterns of *Diaprepes* weevil population related to soil characteristics. Using the moving average forecast model (SAS Institute, 1993), we estimated the future *Diaprepes* population pattern against time (t) as the average of the last N monitoring of the underlying time series, which were the 3-year means of the weekly *Diaprepes* field monitoring data. The simple unweighted moving average model was described by the equation as follows:

$$\mathrm{Dia}_{t+1} = \frac{\overline{\mathrm{Dia}}_t + \overline{\mathrm{Dia}}_{t-1} + \overline{\mathrm{Dia}}_{t-2} + \cdots + \overline{\mathrm{Dia}}_{t-j}}{N}, \tag{1}$$

where Dia_{t+1} is the forecast for the *Diaprepes* root weevil for a future period (week), $\overline{\mathrm{Dia}}$ the 3-year mean of weekly monitoring data of *Diaprepes* root weevil population, t the number of weeks, j the total of consecutive number of weeks of monitoring, and N is the moving average interval of the period (week). We used $N = 2$ in the moving average forecast estimations.

We used PROC EXPAND (SAS Institute, 1993) to generate a new time series of weekly *Diaprepes* weevil population by computation of the moving average of the original series (3-year mean of weekly *Diaprepes* weevil monitoring data in 2001, 2002 and 2003). The standard errors (S.E.) of the unweighted moving average forecast data were also estimated.

3. Results

3.1. Three-year spatial and temporal patterns of Diaprepes root weevil

A total of 962, 945 and 549 *Diaprepes* adult weevils were trapped in 2001 (April–December), 2002 (January–December) and 2003 (January–September), respectively. The mean and standard deviation (S.D.) of adults per $30 \times 12\,\mathrm{m}^2$ (per trap monitoring area), were similar in the first 2 years (Table 1). The sample variance was 80, 73 and 31, which was proportional to adult weevil density across the 3 years. The 3-year mean weevil density was 8.2 ± 6.5 adults per $30 \times 12\,\mathrm{m}^2$ (or 0.023 ± 0.018 weevils m^{-2}). The highest density was 38 adults per $30 \times 12\,\mathrm{m}^2$ (or 0.091 ± 0.027 weevils m^{-2}) in 2001.

Monthly mean root weevil population showed a trend to decrease across the 3 years (24.6, 18.2 and 15.3 adult weevils per trap in 2001, 2002 and 2003, respectively). Differences in monthly mean *Diaprepes* population were significant in 2001 (ANOVA; $F = 12.63$; d.f. $= 8$, 30; $P < 0.0001$), in 2002 (ANOVA; $F = 4.17$; d.f. $= 11$, 40; $P < 0.0004$), and in 2003 (ANOVA; $F = 2.43$; d.f. $= 8$, 27; $P < 0.0403$). The post hoc Tukey test showed that the honestly significant difference (HSD) was 25.8 weevils per month in 2001, 35.8 weevils per month in 2002 and 18.6 weevils per month in 2003. The weekly weevil population peaked in the second week of May in 2001 (103 adults) and in the last week of April in 2002 (112 adults), as shown the timing and variations of weevil density per trap (Fig. 2).

Table 1
Descriptive statistics of weekly *Diaprepes* root weevil population monitored in 2001, 2002 and 2003, gravimetrical soil water content (SWC), time-domain-reflectory volumetric water content (TDR), clay, sand, silt, soil organic matter content (SOM), and Mehlich-I extractable nutrient variables determined in 2003 ($n = 100$)

Variable	Mean	S.D.	Min.	Max.	Kurtosis	Skewness	CV
*Dia*01[a]	9.6	9.0	0	38.0	0.7	1.2	93.2
*Dia*02[a]	9.5	8.5	0	35.0	0.2	1.0	90.3
*Dia*03[a]	5.5	5.6	0	22.0	1.0	1.3	101.3
SWC[b]	0.052	0.038	0.003	0.167	0.294	1.039	73.5
TDR[b]	0.071	0.065	0.020	0.270	2.252	1.735	91.4
Sand[b]	906	44	754	986	0.5	−0.7	4.9
Clay[b]	34	28	1.0	102	−0.2	0.5	83.4
Silt[b]	60	39	8.0	246	5.3	2.0	65.3
SOM[b]	10.1	5.7	2.0	24.7	−0.8	0.4	56.4
CEC[b]	7.8	6.1	1.8	26.5	2.5	1.7	78.2
pH[b]	6.3	0.7	4.8	7.5	−0.9	−0.3	11.8
P[b]	27	16	5.5	70	−0.3	0.6	57.9
K[b]	38	30	5.0	179.5	3.4	1.3	79.0
Mg[b]	78	54	10	237	−0.3	0.8	69.7
Ca[b]	1056	1106	174	4799	4.5	2.3	104.7
Mn[b]	4.2	1.3	1.7	8.0	−0.3	0.2	31.5
Fe[b]	31	6.8	14.1	45.8	−0.2	0.2	22.1

CV: coefficient of variation in %.

[a] Weekly *Diaprepes* adult populations in 2001, 2002 and in 2003, respectively.

[b] SWC, gravimetric soil water content ($\mathrm{kg\,kg^{-1}}$); TDR, volumetric soil water content ($\mathrm{m^3\,m^{-3}}$); sand, clay, silt ($\mathrm{g\,kg^{-1}}$); organic matter content ($\mathrm{g\,kg^{-1}}$); CEC ($\mathrm{Cmol\,kg^{-1}}$); and P, K, Mg, Ca, Mn and Fe ($\mathrm{mg\,kg^{-1}}$).

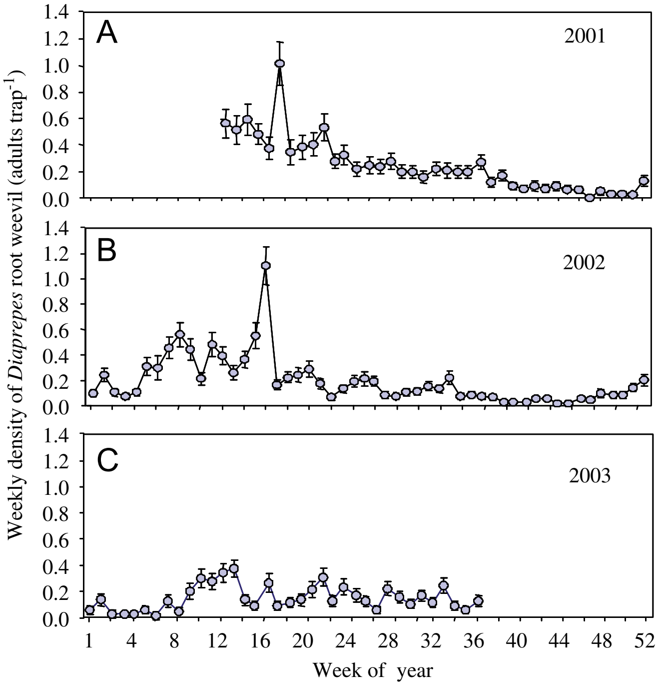

Fig. 2. Temporal patterns of weekly density (mean and S.E., $n = 100$) of *Diaprepes* root weevil adult population in 2001 (A), 2002 (B), and 2003 (C).

Diaprepes root weevil density appeared a prolonged, gradual decrease trend from June to December in 2001 (Fig. 2A). However, it showed a quick decrease pattern from late summer in 2002 (Fig. 2B). The outbreaks of adult weevils in the spring were likely related to the increase of air and soil temperature. The 0.6-m air temperature increased by 12.3 °C to reach 25.6 °C, and soil temperature increased by 14.7 °C to reach 27.9 °C from January to April, which may have contributed to the outbreak of the adult weevil. Peaks of the weevil density in the spring were not related to rainfall. Only the weekly peaks of weevil population in late summer (August and September) occurred with high weekly rainfall (132–180 mm), and the weekly weevil population was strongly correlated with the weekly rainfall during this period ($r = 0.91$).

Spatially, weevil population was more abundant in the east and south than other areas across the field each year (Fig. 3). The higher weevil density was found in the Mollisol soil, and the interpolated areas of high weevil density were limited to the Mollisol (Chobee loam) and some transition areas across the Alfisol (Boca sand) during the 3 years (Fig. 3). Although high weevil density areas changed locations each year, the weevil distribution was not skewed, as shown by the very small kurtosis values (0.22–1.03) in Table 1 (kurtosis < 3, the threshold of skew distribution).

The weevil density was significantly different between soil types (Fig. 4A). Per $30 \times 12\,\mathrm{m}^2$ (per trap area) the weevil density was 14.5, 15.6 and 9.9 weevils ($n = 57$) in the Mollisol against 6.1, 5.0 and 2.3 weevils ($n = 43$) in the Alfisol in 2001, 2002 and 2003, respectively. The Mollisol (Chobee loam) had a significantly higher weevil density than in the Alfisol (Boca sand) in 2001 ($P < 0.0001$, HSD = 2.41 weevils), in 2002 ($P < 0.0004$, HSD = 2.43 weevils) and in 2003 ($P < 0.0065$, HSD = 1.77 weevils).

3.2. *Spatial patterns of soil characteristics*

Among the soil variables, the distribution of silt content, and Ca and K concentrations were positively skewed (kurtosis 3.4–5.3, Table 1) The Alfisol ($n = 43$) and Mollisol ($n = 57$) contained little clay and silt (Fig. 4B). Both soils contained significantly higher sand content with $920\,\mathrm{g\,kg^{-1}}$ in the Alfisol and $888\,\mathrm{g\,kg^{-1}}$ in the Mollisol ($P < 0.0192$), close to the average sand content in Florida citrus soil ($940\,\mathrm{g\,kg^{-1}}$). The soils were slightly acidic (6.3 ± 0.7, Table 1) but the value was in the range of optimum soil pH for citrus production (pH 6.0–6.5). There was no pH difference for the two soils (Fig. 4C). Both soils were very poor in SOM, but the SOM value was more than two times higher in the loamy Mollisol ($14.5\,\mathrm{mg\,g^{-1}}$) than the sandy Alfisol ($P < 0.0001$, Fig. 4C). Gravimetrical SWC and volumetric TDR water content were higher in the Mollisol ($P < 0.0015$, Fig. 4D). Both soils were poor in P, K, Mg and Mn but not in Fe. As a loam, the Mollisol had a significantly higher concentration for all the Mehlich-I extractable nutrients than the sandy Alfisol (Fig. 4E and F). The Ca concentration had the highest S.D. and the highest range among all the soil variables (Table 1) and Ca level was three times higher in the Mollisol ($1766\,\mathrm{mg\,kg^{-1}}$) than in the Alfisol ($520\,\mathrm{mg\,kg^{-1}}$). The Mg concentrations were low but different ($44\,\mathrm{mg\,kg^{-1}}$ in Alfisol and $122\,\mathrm{mg\,kg^{-1}}$ in Mollisol, $P < 0.0001$). As a result, the Ca/Mg ratios in these soils were very high (12/1–14/1).

The interpolated spatial patterns of soil physical and chemical variables matched soil-type boundaries. Higher gravimetrical SWC and volumetric TDR water content, SOM, Mg, K and P were distributed within the loamy Mollisol (Fig. 5), which were comparable to the *Diaprepes* weevil distribution patterns across the 3 years (Fig. 3).

3.3. *Correlations between Diaprepes root weevil and soil variables*

Monthly density of *Diaprepes* adult weevil was correlated at the 100 monitoring traps each year ($0.47 < r < 0.63$, Table 2). The weevil density was correlated with gravimetric SWC, volumetric TDR, sand, clay, SOM, CEC, P, K, Mg and Ca across the 3 years (Table 2). For other soil variables, the weevil was associated with soil pH in 2001, soil Fe in 2002, and soil Mn in 2003. The monthly means of *Diaprepes* root weevil population was associated with all measured soil physical and chemical variables except soil pH and silt content (Table 2).

Soil variables were correlated with each other except for silt and pH ($0.28 < r < 0.98$, Table 3). As the most dynamic variable in the soil, water content (both gravimetric SWC and volumetric TDR) were significantly correlated to sand, clay, SOM, CEC, P, K, Mg, Ca and Fe (Table 3). The

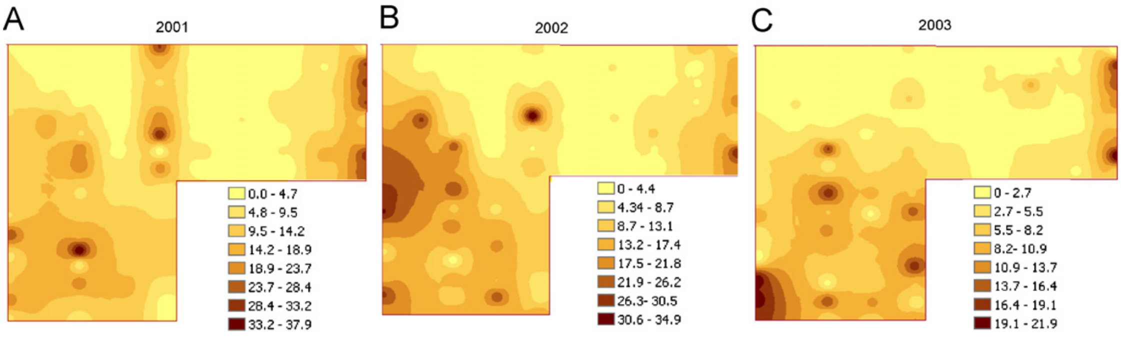

Fig. 3. Interpolated spatial patterns of *Diaprepes* adult root weevil density (adults per $30 \times 12\,\mathrm{m}^2$) in 2001 (A), in 2002 (B), and in 2003 (C).

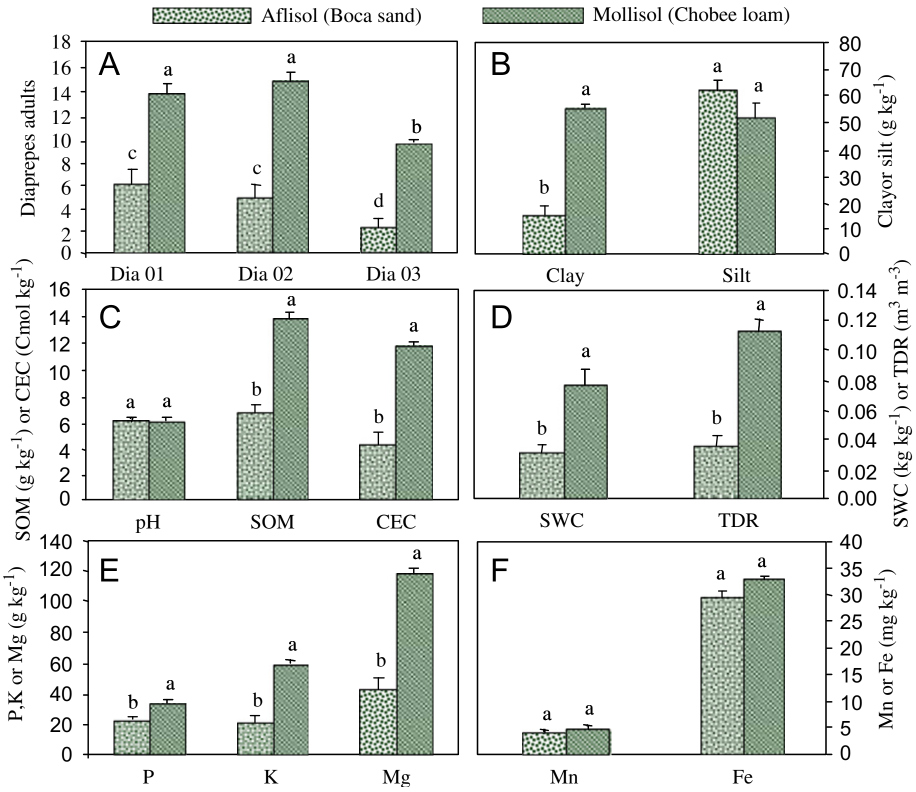

Fig. 4. Mean and S.E. of *Diaprepes* weevil density in 2001 (Dia01), 2002 (Dia02) and 2003 (Dia03)—(A); texture—(B); pH, soil organic matter (SOM) and cation exchange capacity (CEC)—(C); soil water content (SWC) and (TDR)—(D); soil P, K and Mg—(E); and soil Mn and Fe—(F) in Alfisol and Mollisol. Each bar, $n = 57$ for Boca sand (Alfisol) and $n = 43$ for Chobee loam (Mollisol). Post hoc Tukey test honestly significant differences (HSD, $\alpha = 0.05$) are: Dia01 = 2.41 adults, Dia01 = 2.43 adults, Dia01 = 1.77 adults, clay = 7.87 g kg^{-1}, silt = 7.87 g kg^{-1}, pH = 0.33, SOM = 1.38 g kg^{-1}, CEC = 1.97 Cmol kg^{-1}, SWC = 0.012 kg kg^{-1}, TDR = 0.023 m^3 m^{-3}, P = 5.83 mg kg^{-1}, K = 9.38 mg kg^{-1}, Mg = 14.89 mg kg^{-1}, Mn = 0.54 mg kg^{-1} and Fe = 2.51 mg kg^{-1}.

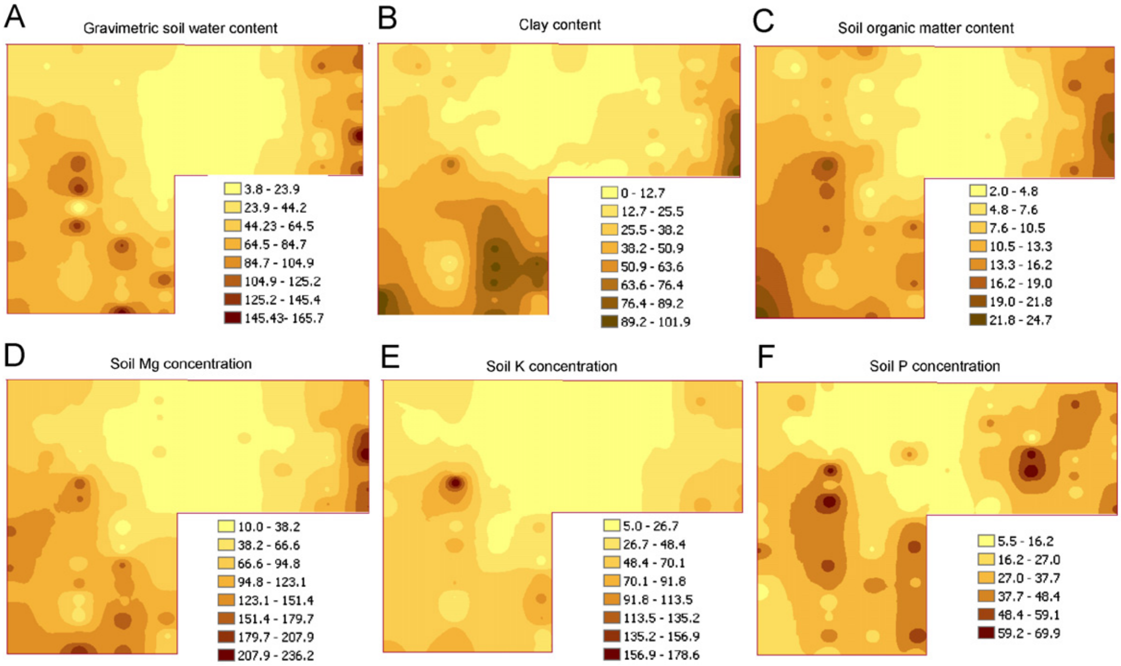

Fig. 5. Interpolated spatial patterns of gravimetric soil water content (kg kg^{-1})—(A), clay content (g kg^{-1})—(B), soil organic matter content (g kg^{-1})—(C), Melich-I extractable soil Mg (mg kg^{-1})—(D), K (mg kg^{-1})—(E) and P concentration (mg kg^{-1})—(F).

correlations of SOM and Mg with all soil variables were strong except with soil pH and silt. The correlation between soil Ca and CEC ($r = 0.98$, Table 3) revealed the importance of Ca concentrations among the nutrients in these slightly acidic Alfisol and Mollisol.

Correlation coefficients of soil variables by soil type (Mollisol or Alfisol) were similar to these for the whole site as shown in Table 2. By importance of the regression relationships (highest R^2 values) among the soil variables, SOM ($\mathrm{g\,kg^{-1}}$) and Mg concentration ($\mathrm{mg\,kg^{-1}}$) would be estimated using SWC ($\mathrm{kg\,kg^{-1}}$) or TDR ($\mathrm{m^3\,m^{-3}}$), described as follows:

$$\mathrm{SOM} = 4974.8\,\mathrm{SWC} + 1242.8 \quad (R^2 = 0.56, P < 0.001, n = 100), \tag{2}$$

$$\mathrm{SOM} = 7438.4\,\mathrm{TDR} - 4377.9 \quad (R^2 = 0.43, P < 0.001, n = 100), \tag{3}$$

$$\mathrm{Mg} = 965.2\,\mathrm{SWC} + 27656 \quad (R^2 = 0.48, P < 0.001, n = 100), \tag{4}$$

$$\mathrm{Mg} = 546.7\,\mathrm{TDR} + 38710 \quad (R^2 = 0.43, P < 0.001, n = 100). \tag{5}$$

Table 2

Correlation between weekly mean *Diaprepes* root weevil density in 2001, 2002, 2003, and 3-year weekly mean *Diaprepes* root weevil density related to gravimetrical soil water content (SWC); time-domain-reflectory volumetric soil water content (TDR); soil texture (sand, clay and silt); organic matter content (SOM); pH, cation exchange capacity (CEC); and macro and minor soil nutrients (P, K, Mg, Ca, Mn and Fe)

Variables	*Dia*01[a]	*Dia*02[a]	*Dia*03[a]	3-year *Dia*[a]
Pearson correlation coefficient (*r*)[b]				
*Dia*02[a]	0.63**	1		
*Dia*03[a]	0.47**	0.56**	1	
3-year *Dia*[a]	0.88**	0.86**	0.77**	1
SWC	0.37**	0.52**	0.42**	0.51**
TDR	0.36**	0.47**	0.39**	0.48**
Sand	−0.34**	−0.34**	−0.33**	−0.40**
Clay	0.38**	0.52**	0.55**	0.56**
Silt	0.11ns	0.01ns	−0.03ns	0.05ns
SOM	0.44**	0.55**	0.55**	0.60**
PH	−0.23*	−0.04ns	−0.11ns	−0.17ns
CEC	0.38**	0.57**	0.54**	0.57**
P	0.23**	0.35**	0.29**	0.34**
K	0.42**	0.53**	0.55**	0.58**
Mg	0.49**	0.65**	0.53**	0.65**
Ca	0.32**	0.52**	0.48**	0.50**
Mn	0.28**	0.26**	0.14ns	0.28**
Fe	0.14ns	0.32**	0.19ns	0.24*

[a] *Diaprepes* root weevil population in 2001, 2002, 2003, and 3-year total population (3-year *Dia*). $n = 100$.

[b] ns, * and **: non-significant and significant at probabilities $P < 0.05$ and $P < 0.01$, respectively.

The semivariagram for the *Diaprepes* weevil varied between 40.8 and 107.1 in 2001, 30.2–94.5 in 2002 and 17.1–44.2 in 2003, which was proportional to the weevil density across these years. The semivariogram for the weevil tended to increase from east to west across the grove, and the autocorrelation range for the weevil (60 m) was within the interpolated distribution pattern of the weevil shown in Fig. 3. The semivariograms for SWC, TDR, clay, SOM, Mg, Ca and K also increased from east to west and their autocorrelation distance was between 60 and 90 m with specific patterns (semivariogram graph not shown).

3.4. Exponential growth model and moving average model

From the start of the year to the population peak in the spring, the captured adult *Diaprepes* weevils showed an exponential pattern each year. Increasing until the population peak (within the first 19–21 weeks), the growth of the weevil population (Dia) with time (*t*, week) was described

Table 3

Linear correlations of gravimetrical soil water content (SWC); time-domain-reflectory volumetric soil water content (TDR); sand, clay, silt, organic matter content (SOM); pH; cation exchange capacity (CEC); and macro and microsoil nutrients (P, K, Mg, Ca, Mn and Fe)

	SWC	TDR	Sand	Clay	Silt	SOM	pH	CEC	P	K	Mg	Ca	Mn	Fe
Pearson correlation coefficient (*r*)[a]														
SWC	1													
TDR	0.86**	1												
Sand	−0.34**	−0.38**	1											
Clay	0.67**	0.67**	−0.48**	1										
Silt	−0.09ns	−0.06ns	−0.78**	−0.17ns	1									
SOM	0.75**	0.66**	−0.42**	0.73**	−0.04ns	1								
pH	−0.11ns	0.03ns	−0.02ns	−0.02ns	0.04ns	−0.22ns	1							
CEC	0.72**	0.70**	−0.48**	0.72**	0.03ns	0.81**	0.19ns	1						
P	0.39**	0.33**	−0.26**	0.39**	0.02ns	0.40**	−0.17ns	0.30**	1					
K	0.63**	0.60**	−0.43**	0.62**	0.05ns	0.72**	−0.34**	0.61**	0.52**	1				
Mg	0.68**	0.66**	−0.48**	0.77**	−0.01ns	0.84**	−0.16ns	0.76**	0.41**	0.76**	1			
Ca	0.64**	0.64**	−0.45**	0.63**	0.06ns	0.71**	0.34**	0.98**	0.21ns	0.49**	0.64**	1		
Mn	0.09ns	0.08ns	−0.10ns	0.17ns	−0.02ns	0.28*	−0.54**	−0.08ns	0.19ns	0.35**	0.50**	−0.21ns	1	
Fe	0.28**	0.34**	−0.32**	0.30**	0.14ns	0.28**	0.67**	0.57**	0.05ns	0.08ns	0.28*	0.69**	−0.22ns	1

[a] n = 100. ns, * and **: non-significant and significant at probabilities $P < 0.05$ and $P < 0.01$, respectively.

by the exponential equations as follows:

$$2001: \quad \text{Dia} = 7.747\,\mathrm{e}^{0.1333t} \quad (R^2 = 0.72, P < 0.01, n = 6), \tag{6}$$

$$2002: \quad \text{Dia} = 8.2465\,\mathrm{e}^{0.1461t} \quad (R^2 = 0.70, P < 0.01, n = 17), \tag{7}$$

$$2003: \quad \text{Dia} = 3.259\,\mathrm{e}^{0.1557t} \quad (R^2 = 0.54, P < 0.05, n = 14). \tag{8}$$

The exponential growth of the *Diaprepes* weevil population showed the best fit by the 3-year mean population ($R^2 = 0.81$, $P < 0.01$, $n = 17$, Fig. 6).

The moving average model forecast using Eq. (1) demonstrates that the future temporal patterns of the *Diaprepes* weevil population would be highly variable with time, comparable to the field observation patterns shown by the 3-year mean weekly *Diaprepes* data (Fig. 7A). Each point in the 3-year field time series dataset is the mean of monitoring data from 39 weeks × 100 traps in 2001, 52 weeks × 100 traps in 2002, and 36 weeks × 100 traps in 2003. The field weekly mean is from $n = 2 \times 100$ for January–March, $n = 3 \times 100$ for March–September, and $n = 2 \times 100$ for September–December. The moving average forecast varies between 16.0 ± 11.9 (range 2.1–52) weevils, which is very close to the mean and S.D. (15.8 ± 12.7 weevils) of the 3-year field dataset. The forecasted peak, with a lag time step of 1 week compared to the field-monitored peak, exhibited a smoother change with time steps than the 3-year field dataset (Fig. 7A). The other smaller forecasted peaks also show the weevil abundance variations in late summer. The S.E. of the moving average forecast data varied between 0.3 and 17 weevils, and the highest S.E. follows the yearly peak in early spring (Fig. 7A). When plotted against the 3-year mean field data, the regression shows that the forecast data are strongly related to the multi-year field monitoring data ($R^2 = 0.88$, Fig. 7B).

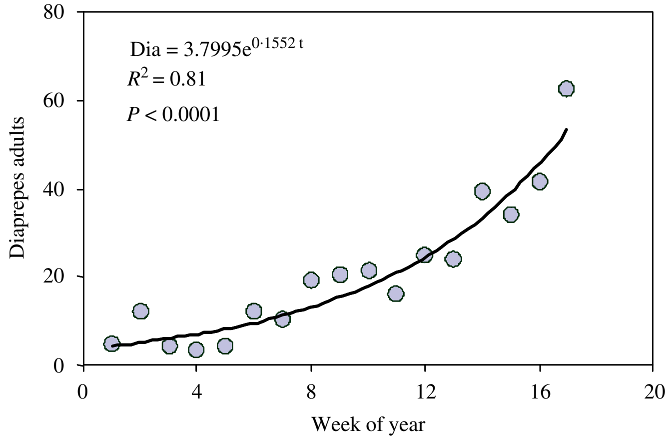

Fig. 6. Exponential growth pattern of *Diaprepes* root weevil population from the start of the season to the yearly peak in the spring. t: time in weeks.

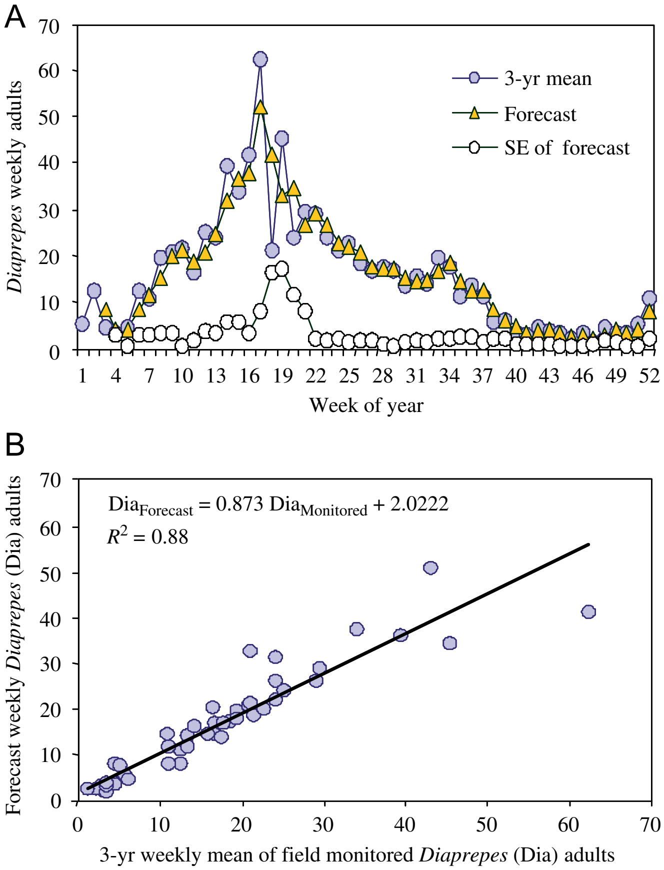

Fig. 7. Moving average model forecast of development patterns of *Diaprepes* adult weevil population and the 3-year mean *Diaprepes* adult population monitored in the grove (A) and regression relationship of the forecast data and the field monitoring data (B).

3.5. Soil characteristics-based simple and multivariate linear soil-Diaprepes models

Using the 3-year mean of weekly *Diaprepes* root weevil population captured in the 100 traps, the parameters of the best-fit models (highest R^2) for the *Diaprepes* variable were SWC, clay, SOM and Mg concentration (Fig. 8). All the regression lines showed a trend to increase with increasing SWC, clay, SOM and Mg concentrations. There was a more pronounced increase of weevil number with higher SOM and Mg concentration ($0.36 < R^2 < 0.44$) with smaller root mean square errors (RMSE, Fig. 8). The simple or polynomial regression showed a significant relationship between the TDR and weevil across the 3 years ($0.17 < R^2 < 0.32$, $P < 0.001$, equations not shown).

By including all significant physical parameters (SWC, clay and sand) or significant chemical parameters (SOM, K and Mg) into stepwise multivariate linear models to estimate the size of the *Diaprepes* weevil population, the model coefficient of determination increased ($R^2 = 0.37$ and $R^2 = 0.46$), along with a smaller RMSE (Table 4). All the estimate parameters and intercepts were significant ($P < 0.0001$).

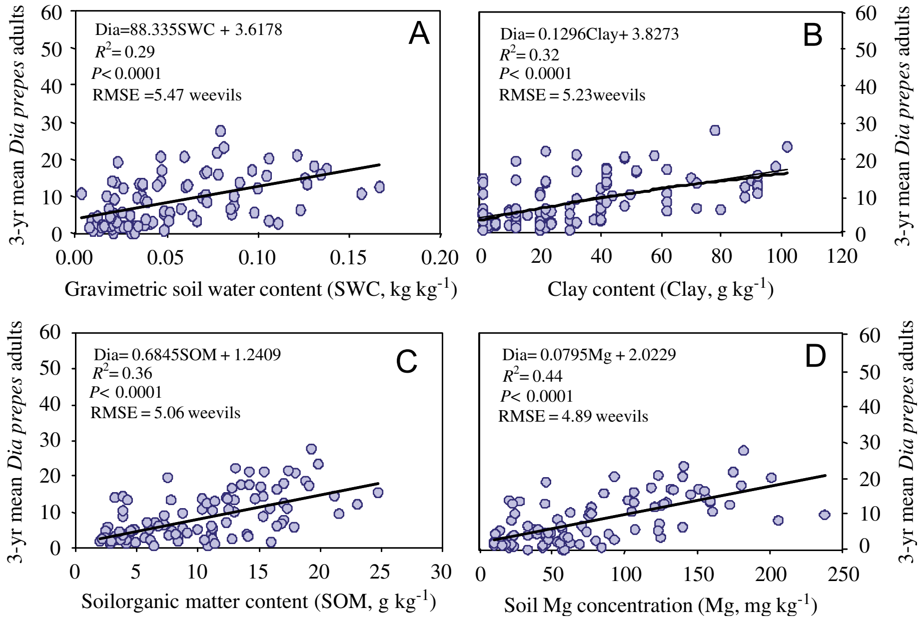

Fig. 8. Regression relationship of 3-year mean weekly *Diaprepes* adult weevil (Dia), gravimetric soil water content (SWC)—(A), clay content—(B), soil organic matter content (SOM)—(C), and soil Mg concentration—(D). RMSE: model root mean square error.

Table 4
Soil physical and chemical characteristics-based multivariate linear models for estimating *Diaprepes* root weevil density population

Multivariate linear models	R^2	RMSE[b]	F	P
Soil physical characteristics-based model equation[a]				
Dia = 2.8816 + 0.04449 SWC + 0.08928 Clay	0.3511	5.2866	26.24	<0.0001
Dia = 37.4139 + 0.07382 SWC−0.03646 Sand	0.3228	5.4005	23.12	<0.0001
Dia = 24.6122 + 0.04340SWC + 0.07263 Clay −0.02329 Sand	0.3704	5.2344	18.82	<0.0001
Soil chemical characteristics-based equation[a]				
Dia = −5.1197 + 0.8553 SOM + 0.9361 pH	0.3152	7.1341	22.3	<0.0001
Dia = 1.2537 + 0.4306 SOM + 0.06720 K	0.4103	5.0395	33.75	<0.0001
Dia = 1.4194 + 0.1229 SOM + 0.05252 Mg + 0.03792 K	0.4565	4.8631	26.88	<0.0001
Soil physico-chemical characteristics-based equation[a]				
Dia = 1.4382 + 0.008528 SWC + 0.01878 Clay + 0.06774 SOM + 0.04683 Mg + 0.03552 K	0.4103	5.0395	33.75	<0.0001
Dia = 1.4595 + 0.002158 TDR + 0.01980 Clay + 0.06774 SOM + 0.04683 Mg + 0.03552 K	0.4601	4.8984	16.02	<0.0001

[a] Dia: 3-year mean *Diaprepes* weevil data ($n = 3 \times 100$, year × trap); SWC: gravimetrical soil water content; TDR: time-domain-reflectory volumetric soil water content and SOM: soil organic matter content

[b] Soil gravimetrical water content, SWC (kg kg^{-1}); clay (g kg^{-1}); sand (g kg^{-1}); soil organic matter, SOM (g kg^{-1}); pH, K and Mg concentrations (mg kg^{-1}); RMSE: Root Mean Square Error.

4. Discussion

4.1. Soil water content, clay, sand, SOM, Mg and Diaprepes weevil relations

The significant correlations between the 3-year weekly mean of *Diaprepes* root weevil, SWC, TDR, clay, sand, SOM, Mg, Ca and K variables in the slightly acidic Alfisol and Mollisol (Table 2) suggested that the correlations between the adult weevil and soil variables were constant from year to year, and that their correlations were not due to chance. One of the explanations for the influence of environmental soil characteristics on adult weevil populations would be that SWC and texture would affect survival of *Diaprepes* larvae (Li et al., 2006a, 2007a, b) and thus, adult weevil populations. In a citrus grove with a strongly acidic Mollisol (pH 4.8), 1 year of *Diaprepes* adult weevil was related to soil Mg and Ca (Li et al., 2004). In another citrus grove with a near neutral Spodosol (pH 6.6), 2 of 3 years of *Diaprepes* adult weevil was associated with sand, SWC, pH and Mg (Li et al., 2007b). The results of this study further support the idea that weevil patterns would be associated with particular soil characteristics where are the citrus trees on which the weevils feed (Li et al., 2004, 2006a, 2007b).

Differences in clay, sand and SOM would cause variability in soil aeration, and water and nutrient availability (Li et al., 2002, 2005, 2006a) to influence citrus tree status, and therefore these variables were among the most important soil parameters associated with *Diaprepes* weevil patterns (Table 2). Better aeration in sandy soil would favor larval survival (survival of *Diaprepes* larvae was 76–85% in a sandy soil against only 58–64% in a loamy soil, Li et al., 2006a) and thus, adult density should be higher in the sandy soil. However, our results showed the opposite with lower weevil density in the sandy Alfisol than in the loamy Mollisol (Fig. 2). An explication would be the poor water holding Alfisol was too dry ($\text{SWC}<0.04\,\text{kg}\,\text{kg}^{-1}$, Fig. 4D), and there was no enough moisture for larval survival. In other studies, bacteria, fungi, nematodes, pH, moisture and SOM, each had a unique distribution pattern (Klironomos et al., 1999) but larval pupal weight was not influenced by soil water availability (Lower et al., 2003). Also, nematode numbers were greater in the surface layer of plots with 35% subsurface clay than in plots with 3% subsurface clay (McSorley and Frederick, 2002).

The strong influence of soil moisture on the adult population in these slightly acidic Alfisol and Mollisol was shown by the significant regression relationship of *Diaprepes* vs. SWC and TDR (Fig. 8). Soil water and *Diaprepes* weevil were highly variable (CV 73.7–101.3%, Table 1), therefore, these two variables were correlated with each other. The higher SWC and TDR in the loamy Mollisol than in the sandy Alfisol (Fig. 4D) was because of its higher clay content (Fig. 4B) and higher SOM (Fig. 4C). Soil organic matter holds water and contains nutrients and thus, SWC and Mg and Ca concentrations were high in the Mollisol. The relationship of SWC and SOM in this slightly acidic (pH 6.3, Table 1) Mollisol was comparable to the results found in a strongly acidic (pH 4.8) Mollisol in another citrus grove, reported in Li et al. (2004).

Soil pH has been among the most important variables related to the emergence of *Diaprepes* weevils from a strongly acidic Mollisol (Li et al., 2005) and to the density of *Diaprepes* adults in a near-neutral Spodosol in citrus groves (Li et al., 2007b). However, soil pH was correlated with the weevil in only 1 year (2001) in these slightly acidic Mollisol and Alfisol (Table 2). The lack of a correlation between pH and the multi-year *Diaprepes* adult population could be because soil pH had little variation as shown by the small S.D. (0.7 units) and small CV (11.8%) in these slightly acidic Alfisol and Mollisol (Table 1). Also, the other difference was that the Mg concentration in the slightly acidic Alfisol and Mollisol were only 20–40% of the Mg level in the strongly acidic Mollisol and the near neutral Spodosol (Li et al., 2007b). The reasons of the low Mg concentration in these slightly acidic Alfisol and Mollisol deserve more future study.

4.2. Implication of the models for controlling Diaprepes root weevil

The outbreak of *Diaprepes* adult weevils from the start of the year (mid-February) to the peak in the spring (April–May) exhibited an exponential trend of insect growth (Fig. 6). The growth of a population was exponential in theory when populations were in the initial growth phases at the start of the season when competition and damage-induced plant stress should have less influence (Byers and Castle, 2005). Our data showed that the outbreaks of soil-inhabiting *Diaprepes* root weevil could occur between April and May when soil temperatures increased from 19.8 °C in February to 27.6 °C in April. Insect growth and plant functions are regulated by temperature. Each species, whether a plant, a larva, or an adult weevil is adapted to grow best over certain minimum temperatures and essentially ceases growth at its maximum temperature (Mattson and Haack, 1987; Li et al., 2007c). The exponential equation ($R^2 = 0.81$, Fig. 6), obtained with the 3-year mean of weevil monitoring data, suggested the best timing of insecticide application was when the weevil numbers are at their highest in the spring (late April).

Models probably would be adequate for a specific situation in predicting populations, their damage and control costs (Byers and Castle, 2005). For practical management, our moving average forecast model (Fig. 7), established using the 3-year weekly mean of field monitoring data, would be useful for predicting future development of the weevil population across a period of a year. The model has generated the new series by computing moving averages of the original series monitored across the 3 years. The moving average model removed seasonal and irregular variation to show the smoothed trend patterns (Fig. 7), which quantified the variability (growth, peak and decrease) of weevil development for making management decisions. For example, historically this grove has been sprayed with four applications of insecticides each year with one application in each season. However, such equal timing of insecticide applications would not be efficient based on the weevil temporal pattern (Fig. 2). The forecast trend (Fig. 7) suggests that insecticides should be applied in the spring, in the summer, and early in the fall. Also, higher rates of insecticides should be applied in the spring, and lower rates should be applied in the summer and in the fall. Such rates need to be further determined in future study.

The spatial pattern of weevils with soil units (Fig. 2) also suggests that insecticide applications should be variable not only in time but also in space. The weevil density was high in the loamy Mollisol (Fig. 2) and therefore higher rate of insecticides should be applied in the Mollisol area. The sandy Alfisol would require a smaller concentration of insecticides because of the lower weevil population density (Fig. 2). A site-specific rate of insecticide applications should be more logical and appropriate than an uniform rate for the whole grove. In addition, the Mollisol boundary is likely a suitable reference for delineating management zones. As shown in Fox et al. (2004), a soil line technique defining relationships of soil characteristics and vegetation indices would provide a means for directing systems management. Also, interfacial boundaries of soil properties and soil units identified using interpolation techniques were suitable entities for management in production systems (Alphen Van and Stoovogel, 2000; Li et al., 2005). Controlling the root weevil using the interpolated patterns (Fig. 3) should be more practical and less costly.

Because of the correlation between root weevil, soil water, texture and nutrients for the whole grove (Table 2), it was not necessary to establish soil variable-based models for each soil type. The SWC, TDR, clay, SOM, Mg and K concentrations were high in the loamy Mollisol, thus the estimations of weevil numbers by the simple or multivariate linear equations (Table 4) should be high for the loamy Mollisol. The multiple linear models have increased the model predictive power (R^2) compared to the simple linear models (Table 4). More spatial variables were included and thus, more variations in the data were explained in the multiple linear models. However, from practical point of view, simple linear models are more comprehensive in showing the relationship between two variables. These simple linear models are easier to understand, more practical, and less costly to put into practice in predicting and controlling the outcome of pest population in the future (Li et al., 2007b). Also, there will be a need of further examination of correlation between *Diaprepes* root weevil, soil N, microbial biomass C and nematode levels in the soil. These variables are important to tree root status and larval survival.

Future study will also include the development of independent datasets from similar sites for validations of our *Diaprepes* root weevil time series forecast model and SWC and SOM-based simple and multivariate linear models. Models are often incorporated in a decision-making framework (Worner, 1991; Tobin et al., 2001; Li et al., 2006b, 2007b). Model predictions of fungi infestations by finding the best-fitting parameters (plots of soil moisture and relative humidity), were close to the 3-year field observations (Weseloh, 2002). The development and resistance to crop rotation of a western corn rootworm population were also adequately predicted using parameters of population density and initial allele frequency in a time-step model (Crowder and Onstad, 2005). Since citrus growers need regular soil testing to determine soil physical and chemical conditions for tree fertilization purposes, soil characteristics-based models would be useful for forecasting future *Diaprepes* weevil patterns in any specific site for reducing labor cost for weevil control. Our exponential growth model (Fig. 6), moving average forecast (Fig. 7) and soil characteristics-based simple and multivariate models (Table 4), have the implications for variable rate and less frequent sprays to contribute to pesticide risk reduction.

5. Conclusions

The relationships between time, soil physical and chemical variables and multi-year *Diaprepes* root weevil dynamic patterns in the sandy Alfisol and loamy Mollisol, yielded insights for development of a time series model and soil characteristics-based models for future management of citrus root weevil. The correlations of multi-year *Diaprepes* root weevil and soil variables were the basis for establishing the process model and the regression models. Soil water could be critical to sustaining productivity of ecosystems in areas with high rainfall and low elevation. As a result, SWC became an important component related to *Diaprepes* weevil population in these slightly acidic Alfisol and Mollisol. The *Diaprepes* root weevil time series model and soil characteristics-based simple and multivariate linear models have the implication in timing of efficient treatment applications before the outbreaks of soil-inhabiting insect pest. The model predictions have the potential for less frequency of spraying from excess use of costly pesticides that can harm the environment, and for reducing field insect monitoring that is time consuming. With site-specific management based on soil and landscape characteristics, these simple and multivariate linear models could be appreciated to put into practice for pest control in the future. It was suggested that using field pest monitoring data and easily measured soil characteristics such as TDR to create site-specific mathematical models could be useful for pest management through estimates of pest dynamical patterns in space and time. Combining time series and environmental soil variability based models to predict temporal and spatial pest patterns would be useful for reducing the cost of field monitoring and for site-specific management of the pest. These models have implications for site-specific variable rates and less frequent sprays to lower environmental pressure and costs from insecticides by conventional applications.

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References

Alphen Van, B.J., Stoovogel, J.J., 2000. A function approach to soil characterization in support of precision agriculture. Soil Science Society of America Journal 64, 1706–1713.

Byers, J.A., Castle, S.J., 2005. Areawide models comparing synchronous versus asynchronous treatments for control of dispersing insect pests. Journal of Economic Entomology 98, 1763–1773.

Crowder, D.W., Onstad, D.W., 2005. Using a generational time-step model to simulate dynamics of adaptation to transgenic corn and crop rotation by western corn rootworm (Coleoptera: Chrysomelidae). Journal of Economic Entomology 98, 518–533.

Fay, P.A., Hartnett, D.C., Knapp, A.K., 1996. Plant tolerance of gall-insect attack and gall-insect performance. Ecology 77, 521–534.

Fox, G.A., Sabbagh, G.J., Searcy, S.W., 2004. An automated soil line identification routine for remotely sensed images. Soil Science Society of America Journal 68, 1326–1331.

Graham, J.H., Bright, D.B., McCoy, C.W., 2003. *Phytophthora–Diaprepes* complex: *Phytophthora* spp. relationship with citrus rootstocks. Plant Disease 87, 85–90.

Horwitz, W. (Ed.), 2000. Official Methods of Analysis of the Association of Official Analytical Chemists (AOAC), 17th ed., vols. 1–2. AOAC, Gaithersburg, MD.

Klironomos, J.N., Rillig, M.C., Allen, M.F., 1999. Designing belowground field experiments with the help of semivariance and power analyses. Applied Soil Ecology 12, 227–238.

Lapointe, S.L., 2000. Thermal requirements for development of *Diaprepes abbreviatus* (Coleoptera: Curculionidae). Environmental Entomology 29, 150–156.

Li, H., Lascano, R.J., Booker, J., Wilson, T.L., Bronson, K.F., Segarra, E., 2002. State-space description of field heterogeneity: water and nitrogen use in cotton. Soil Science Society of America Journal 66, 585–595.

Li, H., Syvertsen, J.P., Stuart, R.J., McCoy, C.W., Schumann, A.W., Castle, W.S., 2004. Soil and *Diaprepes abbreviatus* root weevil spatial variability in a poorly drained citrus grove. Soil Science 169, 650–662.

Li, H., Syvertsen, J.P., Stuart, R.J., McCoy, C.W., Schumann, A.W., 2005. Delineating root weevil management zones in citrus using overlay patterns of soil organic matter content, electrical conductivity and *Diaprepes* adult population. In: Mulla, J., et al. (Eds.), Proceedings of the Seventh International Conference on Precision Agriculture, ASA, CSSA, and SSSA, Madison, WI, pp. 1962–1971.

Li, H., Syvertsen, J.P., McCoy, C.W., Stuart, R.J., Schumann, A.W., 2006a. Water stress and root injury from simulated flooding and *Diaprepes abbreviatus* root weevil larval feeding in citrus. Soil Science 171, 138–151.

Li, H., Parent, L.E., Karam, A., 2006b. Simulation modeling of plant and soil nitrogen use in a potato cropping system in the humid and cool environment. Agriculture Ecosystems & Environment 115, 248–262.

Li, H., McCoy, C.W., Syvertsen, J.P., 2007a. Controlling factors of environmental flooding, soil pH and *Diaprepes abbreviatus* (L.) root weevil feeding in citrus: larval survival and larval growth. Applied Soil Ecology 35, 553–565.

Li, H., Futch, S.H., Stuart, R.J., Syvertsen, J.P., McCoy, C.W., 2007b. Associations of soil iron with citrus tree decline and variability of sand, soil water, pH, magnesium and *Diaprepes abbreviatus* root weevil: two-site study. Environmental & Experimental Botany 59, 321–333.

Li, H., Futch, S.H., Syvertsen, J.P., 2007c. Cross-correlation patterns of air and soil temperatures, rainfall and citrus *Diaprepes abbreviatus* root weevil. Pest Management Science, in press.

Lower, S.S., Kirshenbaum, S., Orians, C.M., 2003. Preference and performance of a willow-feeding leaf beetle: soil nutrient and flooding effects on host quality. Oecologia 136, 402–422.

Mattson, W.J., Haack, R.A., 1987. The role of drought in outbreaks of plant-eating insects. BioScience 37, 110–118.

McCoy, C.W., Stuart, R.J., Nigg, N.N., 2003. Seasonal life stage abundance of *Diaprepes abbreviatus* (L.) in irrigated and non-irrigated citrus plantings in central Florida. Florida Entomologist 86, 34–42.

McSorley, R., Frederick, J.J., 2002. Effect of subsurface clay on nematode communities in a sandy soil. Applied Soil Ecology 19, 1–11.

SAS Institute, 1990. SAS/STAT User's Guide. vol. 2, GLM-VARCOMP, Vers. 6, fourth ed. SAS Institute, Cary, NC.

SAS Institute, 1993. SAS/ETS User's Guide, Vers. 6, second ed. SAS Institute, Cary, NC.

SAS Institute. 1996. SAS/STAT Technical Report: Spatial Prediction Using the SAS System. SAS Institute, Cary, NC.

Tobin, P.C., Nagarkatti, S., Saunders, M.C., 2001. Modeling development in Grape Berry Moth (Lepidoptera: Tortricidae). Environmental Entomology 30, 692–699.

USDA-NRCS, 2003. Keys to Soils Taxonomy, ninth ed. USDA, Washington, DC.

Weseloh, R.M., 2002. Modeling the impact of the fungus *Entomophaga maimaiga* (Zygomycetes: Entomophthorales) on *Gypsy moth* (Lepidoptera: Lymantriidae): incorporating infection by conidia. Environmental Entomology 31, 1071–1084.

Worner, S.P., 1991. Use of models in applied entomology: the need for perspective. Environmental Entomology 20, 768–773.