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CORRELATION OF SOIL CHARACTERISTICS AND *DIAPREPES ABBREVIATUS* ROOT WEEVIL POPULATIONS IN A POORLY DRAINED CITRUS GROVE

HONG LI[1], JAMES P. SYVERTSEN, ROBIN J. STUART,
CLAY W. MCCOY, ARNOLD W. SCHUMANN
AND WILLIAM S. CASTLE
University of Florida, IFAS
Citrus Research and Education Center
Lake Alfred, FL 33850

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Abstract. **A study of soil characteristics, tree health, and *Diaprepes abbreviatus* (L.) root weevil (DRW) distribution was conducted in a poorly drained and declining citrus grove of 'Hamlin' orange on Swingle citrumelo rootstock (*Poncirus trifoliata* (L.) Raf. × *Citrus paradisi* Macfad.) in Osceola County, Florida, in 2002. Weevil adult populations were monitored from April through October with 50 Tedders traps arranged in five 10-trap transects and comprising a 35 × 25 m grid across the grove. Tree health was scored visually from slightly declined to severely declined using a four-point rating system. Soil electrical conductivity was measured using electromagnetic induction EM38 in each row throughout the grove. Soil organic matter, pH, cation exchange capacity (CEC), base saturation, major and minor cations (P, K, Mg, Ca, B, Zn, Mn, Fe, Cu), soil water content, water table depth, and soil texture and composition were measured at each Tedders trap location. Weevil adults were most abundant in the southwestern portion of the grove, and the adult population reached its yearly peak in June. Weevil abundance was not correlated with tree health at specific Tedders trap locations but was negatively associated with soil Mg, Ca, CEC, and H ($P < 0.05$); and tree health was negatively correlated with Fe ($P < 0.05$). It is suggested that DRW management at the field scale could be related to soil liming history, soil flooding, and rain or water erosion might be factors influencing DRW distribution at the field scale but further study is necessary to confirm these relationships.**

Florida citrus soils range from well-drained Entisols on relatively high, rolling landscapes to poorly-drained Alfisoils and Spodosols on low-lying flatwoods (Obreza and Collins, 2002). Recently, the root weevil, *Diaprepes abbreviatus* (L.) (Coleoptera: Curculionidae), has become a major pest of citrus and other agricultural crops in Florida (Graham et al., 2003; McCoy et al., 2003; Nigg et al., 2001; Stuart et al., 2003). *Diaprepes* root weevil (DRW) adults feed on leaves of all citrus varieties and deposit eggs in masses glued between leaves in the citrus canopy (McCoy et al., 2003; Stuart et al., 2003). Hatching neonates fall to the soil surface, and move into the soil where they feed on roots and subsequently pupate (McCoy et al., 2003; Nigg et al., 2001; Stuart et al., 2003). DRW larvae can consume from 3-12% (Li et al., 2003) to 20-80% (Rogers et al., 2000) of the roots of citrus seedlings within six weeks of infestation. However, the decline of mature trees is not apparent until the larvae are well-established on the roots and extensive damage has occurred (Adair et al., 2000). In the absence of early detection methods and effective management tools, infested trees often decline to an unproductive state because of DRW damage and frequently associated *Phytophthora* infections (Graham et al., 2003).

Since DRW larvae, pupae and teneral adult stages occur in soil, the spatial distribution of these developmental stages could be linked to soil variability. Soil and weevil management requires an understanding of soil and plant characteristics as well as DRW population variation in space and time. No previous studies have attempted to quantify the effects of soil conditions on DRW distribution. In Florida citrus, Tedders traps have been shown to be effective tools for monitoring DRW populations (Duncan et al., 2001; McCoy et al., 2003; Stansly et al., 1997). DRW population levels appear to be highest in poorly drained heavy soils, and soil texture has been implicated as a major cause of variation in control of DRW larvae by entomopathogenic nematodes (Duncan, 2003). In field and laboratory studies, mortality of DRW larvae treated with nematodes ranged from 66-80% in sandy soils compared to only 17% in loamy soils (Duncan, 2003). Soil moisture and temperature appear to be important factors for DRW adult emergence from soil (McCoy et al., 2003) and ant predation on DRW neonate larvae (Stuart et al., 2003). However, the movement and dispersal of DRW are not well understood (Nigg et al., 2001; Stansly et al., 1997), and the relationship between other physical and chemical properties of the soil and DRW distribution remains unknown.

We hypothesized that DRW population distribution might be related to spatial variability of soil characteristics such as electrical conductivity (EC), soil organic matter (SOM), soil water content (SWC), water table depth, pH, and major and minor cations (P, K, Mg, Ca, B, Zn, Mn, Fe, Cu). Soil EC, a measure of soil conductance, could be used to quickly evaluate current soil variability. The objectives of the present study were to (i) rate tree health and map the location of rated trees, (ii) assess soil physical and chemical characteristics, and DRW distribution patterns and (iii) determine the correlation coefficients of soil characteristics, tree health, and weevil abundance. This information could be useful in developing improved DRW management related to soil variability at the field scale.

Materials and Methods

Study site description. The study was conducted in 2002 near Poinciana, Osceola County, Fla. (28°22'N, 81°58'W), in a 'Hamlin' orange (*Citrus sinensis* (L.) Osb.) grove on Swingle citrumelo rootstock (*Poncirus trifoliata* (L.) Raf. × *Citrus paradisi* Macfad.). The 9.5-ha study area slopes between 1-3%, and the grove is partially flooded after heavy rainfall periods each year (annual rain = 1380 mm). The soils, classified as Siliceous, Hyperthermic, Arenic Argiaquolls (SCS, 1979), consist of sand muck over clayey materials. Across the study site there are three soil types: Floridana fine sand, covering 80% of the study

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[1]Corresponding author; e-mail: hongli@crec.ifas.ufl.edu.

areas; Pineda fine sand, 15%; and Kaliga muck, 5%. Pineda sand and Kaliga muck are frequently associated with Floridana sand (SCS, 1979). These soils were formed in the flatwoods in sandy marine sediments at the edge of Lake Tohopekaliga.

The grove consisted predominantly of 20-year old orange trees planted in two-row beds. There were 1409 mature trees, 64 gaps where trees had been removed, 758 young trees, and 13 reset trees in the study area (Fig. 1). The missing trees were removed to evaluate DRW life stages in the last several years (McCoy et al, 2003), and the young trees were added in 2000 for further IPM studies. The existing mature trees were generally in decline and had been damaged by DRW during the previous 10 years. The grove was commercially abandoned in 2002. The soil in this grove has been reported to contain over 50 DRW larvae per m^3 based on tree removal and sieve sampling of the soil associated with the central root area (n = 60

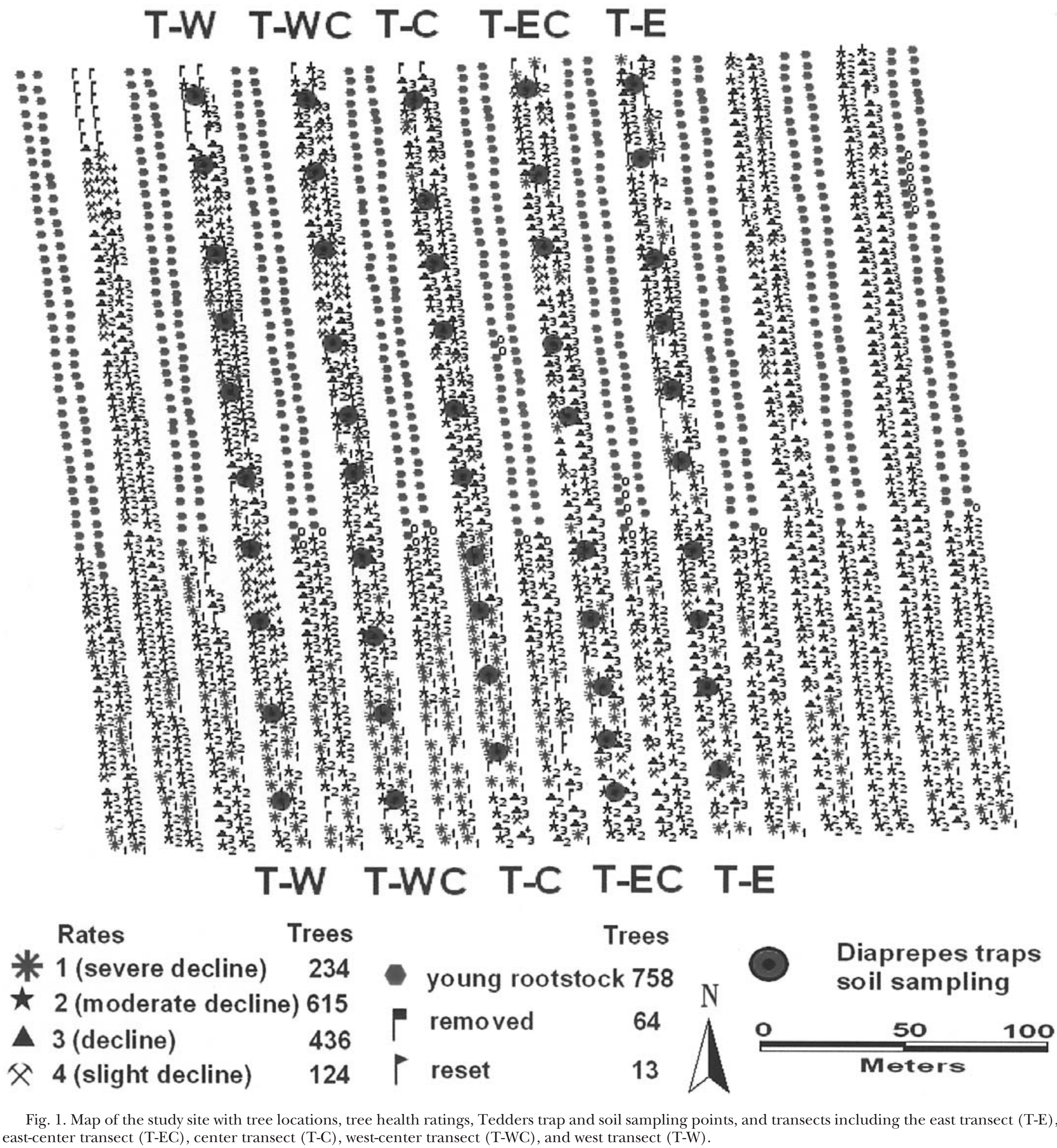

Fig. 1. Map of the study site with tree locations, tree health ratings, Tedders trap and soil sampling points, and transects including the east transect (T-E), east-center transect (T-EC), center transect (T-C), west-center transect (T-WC), and west transect (T-W).

trees, McCoy et al., 2003). During the study period, mature trees were irrigated but received no chemical treatments for pest control. Young trees received regular grove care including liming (dolomite at uniform rate), irrigation (microsprinkler at regional rate), fertilization (standard citrus mixture of 10-2-10-7-12 (N-P-K-S-Zn) at a rate of 0.72 kg per tree with 4 applications per year), regular herbicide (glyphosate at standard rate) within the tree rows, and pest control. The whole field was mowed regularly to maintain ground cover.

Tree, adult weevil, and soil characteristics assessments. Tree health was determined for all mature trees by visual assessment using a numerical 1-4 ranking system as follows: 1 = severe decline (canopy easily seen through, flush on major limbs only or on less than half of the tree, leaves small); 2 = moderate decline (canopy easily seen through, flush on secondary and higher limbs scattered around the entire canopy, leaves small); 3 = decline (well-defined canopy, more than half of which cannot be seen through, flush on secondary and higher limbs, leaves large); and 4 = slight decline (well-shaped and well-defined canopy that cannot be seen through, flush on secondary and higher limbs, leaves large and fully green). The classified trees were geo-referenced using a Garmin handheld GPS12 system (Garmin International, Olathe, KS).

DRW adults were monitored weekly using modified pyramidal Tedders traps as described in Tedders and Wood (1994) and McCoy et al. (2003). Tedders traps were placed near tree trunks about 25 m apart in five 10-trap transects along five mature-tree beds (Fig. 1). Trap geo-positions were located using the Garmin GPS12 system. The 10 Tedders traps in each transect (T) formed a 35 × 25 m grid pattern, and will be referred to as east transect (T-E), east-center transect (T-EC), center transect (T-C), west-center transect (T-WC), and west transect (T-W) (Fig. 1). Counts of adult DRW captured in Tedders traps were made weekly from March through Oct. in 2002 (n = 30 counts per trap). All trapped adults were identified as male or female.

Soil electrical conductivity (EC) was determined using an electromagnetic EM38 instrument (Geonics Limited, Mississauga, Ont., Canada) in each row across the field on 17 Oct. 2002. The EM38 uses electromagnetic induction as a noninvasive method to determine soil EC at two depths, 0-0.3 m and 0-0.9 m. The EM38 measurements were taken at a tractor ground speed of 5 $m \cdot s^{-1}$. The EM38 unit was integrated with a global positioning system (GPS) and a data logger to create a field-scale EC map.

Soils were sampled at each Tedders trap location on 2 Nov. 2002 using a hand probe (6 cm in diameter) from the surface to 1.2 m in 0.3 m increments. A mixed soil sample was taken for each depth (0.3 m) at each site. Soil water table level was measured at the time of soil sampling based on the depth of soil water saturation. Soil samples were air dried. For the top soil (0-0.3 m), we determined gravimetric soil water content (SWC), soil organic matter content (SOM), sand, clay, silt, pH-H2O, cation exchange capacity (CEC), base saturation (BS), and major and minor cations (P, K, Mg, Ca, B, Zn, Mn, Fe and Cu). For soils at depths of 0.3-1.2 m, we determined SWC and pH. Soil texture was determined using the hydrometer method (Horwitz, 2000). The Mehlich I extracted cations and anions (P, K, Mg, Ca, B, Zn, Mn, Fe and Cu) were analyzed using inductively coupled argon plasma emission spectrophotometer, and SOM was determined using the combustion method (Horwitz, 2000) by Waters Agricultural Laboratories (Camilla, GA).

Descriptive statistics, ANOVA, and correlation analysis were conducted using PROC UNIVARIATE, PROC ANOVA, and PROC CORR (SAS, 1990). Tree locations, tree health rates, Tedders trap locations, and the soil sampling grid were mapped using Arcview GIS 3.2 (ESRI Inc., Redlands, Calif.).

Results

Spatial and temporal distribution patterns of Diaprepes adult populations. A total of 234 of the 1409 mature trees (16.6%) were considered severely declined. Moderately declined trees represented 43.6% of the total trees, declined 30.9%, and slightly declined 8.8%. Severely and moderately declined trees were mainly situated in the southwestern portion of the grove, extending ca. 120 m to the north and including the southern portions of transects T-W, T-WC and T-C (Fig. 1).

A total of 1400 DRW adults were captured in Tedders traps (mean ± SD = 28 ± 22 weevils per trap). The total trap counts were highly variable among locations as indicated by a high coefficient of variation (Table 1). Males totaled 946 (19 ± 14 weevils per trap) and females 454 (9 ± 9 weevils per trap); and the sample variance was greater for males (186) compared to females (78). Males represented 67.6% of the total population. The number of males and females captured was generally proportional among traps.

Spatial distribution of DRW adults varied among and along transects (Figs. 2 and 3). There were significant differences in trap catches among transects (ANOVA, $F = 3.74$, $df = 4, 36$, $P = 0.0121$; Fig. 3a), and more weevils tended to be trapped in the three western transects compared to the two eastern transects. Trap catches also tended to increase from

Table 1. Mean, standard deviation (SD) and coefficient of variation (CV) of *Diaprepes* root weevil (DRW) and soil property variables. SOM, soil organic matter; EC, electrical conductivity; BS, base saturation; CEC, cation exchange capacity.

Variables	Mean	SD	CV (%)	Variables	Mean	SD	CV
Diaprepes	28	22	79		mg kg^{-1}		(%)
Water table depth (m)	0.9	0.2	22	P	22	12	55
Moisture ($kg \cdot kg^{-1}$)	0.26	0.08	31	K	114	42	37
Sand (g kg^{-1})	527	174	33	Mg	260	94	36
Clay (g kg^{-1})	323	143	44	Ca	1263	512	41
Silt (g kg^{-1})	154	44	29	B	0.3	0.2	67
pH	4.9	0.4	8.2	Zn	3.1	2.4	77
SOM (g kg^{-1})	80	30	37	Mn	5.5	2.1	38
CEC (Cmol kg^{-1})	15	4.0	26	Fe	36	14	39
EC (mS m^{-1})	35	10	30	Cu	0.1	0.07	70
BS (%)	57	9.3	16	H (%)	21	4.6	22

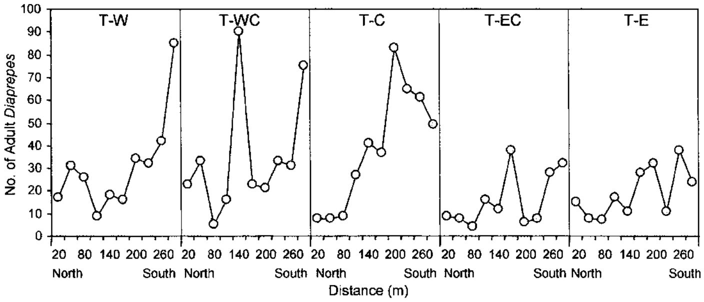

Fig. 2. Total number of adult *Diaprepes* captured in Tedders traps from north to south on the west transect (T-W), west-center transect (T-WC), center transect (T-C), east-center transect (T-EC) and east transect (T-E).

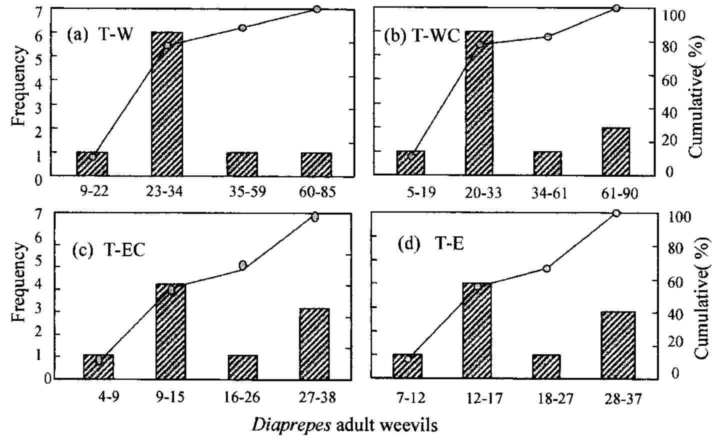

Fig. 4. Distribution frequencies of adult *Diaprepes* on the west transect (T-W, a), west-center transect (T-WC, b), east-center transect (T-EC, c), and east transect (T-E, d).

north to south (ANOVA, $F = 3.60$, $df = 9, 36$, $P = 0.0028$; Fig. 3b). The three western transects constituted the high density area for adults, and 75.9% of the captured weevils came from these transects. There were greater intra-transect variations in the high density area (e.g., T-W, CV = 76%; T-EC, CV = 75%) than in the low density area (e.g., T-E, CV = 56%). Intra-transect distribution frequencies of trapped adults varied among transects (Fig. 4). On the T-W and T-WC transects, 85% of the traps caught 23-85 and 20-90 weevils, respectively (Fig. 4a, b), whereas on the T-EC and T-E transects, 40% of the traps caught 9-15 and 12-17 weevils, respectively (Fig. 4c, d).

There were significant differences in DRW abundance among months (ANOVA, $F = 12.73$, $df = 6, 343$, $P = 0.001$; Fig. 5) with the highest weevil catches occurring in June (450 weevils, n = 200 trap counts). On a monthly basis, the greatest variation in adult weevils was in April (CV = 250%), and the lowest in June (CV = 86%). On a weekly basis, the number of adults trapped varied between 1 and 128 weevils. The adults appeared in the first week of April (1 weevil, n = 50 traps), and numbers increased from mid-May (25 weevils, n = 50 traps) to reach a weekly peak in mid-June (128 weevils, n = 50 traps). Following a decrease from mid-June to the first week of Sept. (37 weevils, n = 50 traps), a second smaller weekly peak of adult emergence appeared in mid-Sept. (91 weevils, n = 50 traps), followed by a further decline thereafter (weekly data not shown).

Spatial patterns of soil variables. Soil physical characteristics (0-0.3 m) were marked by a low and variable sand content (530 ± 170 g·kg^{-1}) and high soil water content (0.26 ± 0.077

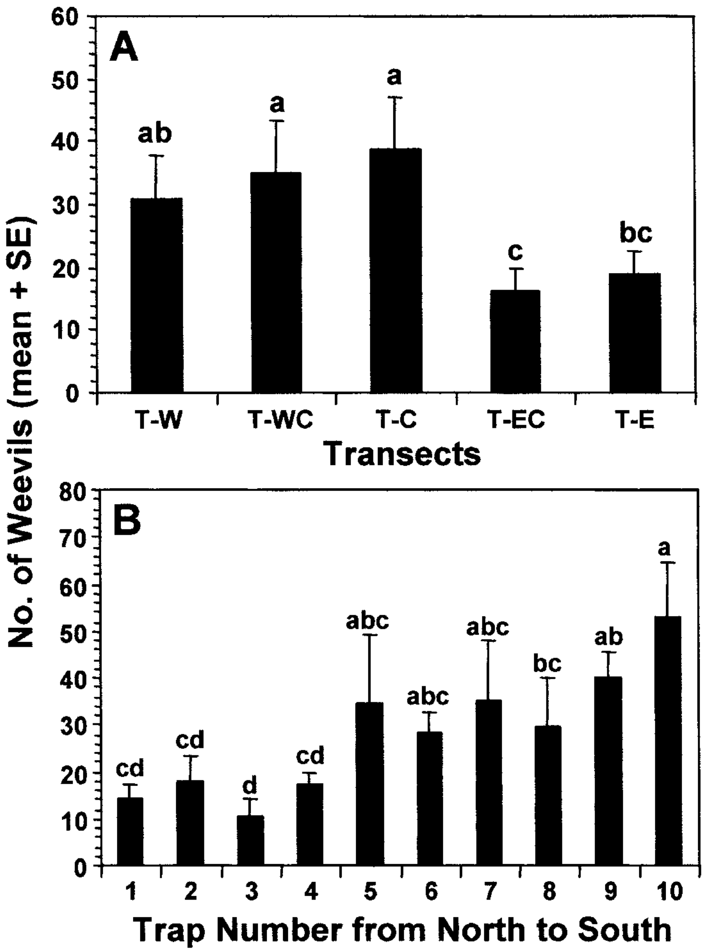

Fig. 3. Comparison of the number of adult *Diaprepes* root weevils captured in Tedders traps among transects (A) and along transects from north to south (B). Bars with common letters are not significantly different ($P = 0.05$) based on ANOVA and LSD tests.

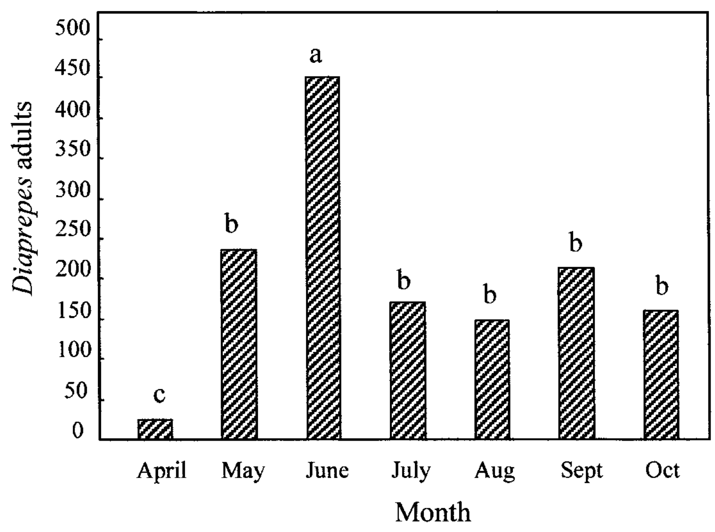

Fig. 5. Monthly counts of *Diaprepes* root weevil adults captured in Tedders traps based on weekly counts of 50 traps (May and July n = 250 trap counts; April, June, Aug., Sept and Oct. n = 200 trap counts). Bars with common letters are not significantly different ($P = 0.05$) based on ANOVA and LSD tests.

m^3·m^{-3}) across the field (Table 1). The sand content was low compared to the average sand content (940 g·kg^{-1}) in citrus soils in Florida (Obreza and Collins, 2002). The measured water table depth corresponded to soil survey data (SCS, 1979). Soil pH was uniform (CV = 8.2%, Table 1) but the value was much lower than the optimum soil pH for citrus production (pH 6.0-6.5, Obreza and Collins, 2002). Soil organic matter content was high and variable (80 ± 30 g) across the field (Table 1). The soil contained large amounts of exchangeable Mg, Ca and Fe, but these properties were variable based on their standard deviations (Table 1). The soil was poor in micronutrients (Zn, Mn, and Cu). Among the soil parameters, P, B, Zn, and Cu were the most variable based on their coefficients of variation (55-99%, Table 1); and water table depth, water content, silt, CEC, EC, BS and H were relatively uniform (CV < 30%).

Spatial patterns of SWC and SOM were comparable across the field (Fig. 6). There were three similar low areas of SWC and SOM, and each appeared in the south on TW, T-WC and TEC (Fig. 6a, b). The soil EC pattern was also similar to the pattern of SOM; and soil CEC was proportional to EC along transects (graphs not shown). Sand content showed an opposite pattern to clay content, and there were consistent and proportional increases and decreases along transects (graphs not shown).

Correlation of soil and Diaprepes variables. Diaprepes abundance was not correlated with tree health at particular Tedders trap locations but was negatively correlated with CEC, Mg, Ca and H (Table 2). Adult weevils were found within a soil Mg concentration range of 10-500 mg·kg^{-1}. Tree health was negatively correlated with soil Fe; and Fe was correlated with water table depth (Table 2). Soil water content (SWC) was negatively correlated with sand and positively correlated with SOM, CEC, EC, K, Mg, Ca and B (Table 2). The SOM was positively associated with clay, SWC, CEC, EC, K, Mg, Ca and B, and negatively associated with pH and Fe ($-0.25 < r < 0.90$, Table 2). Correlations between pH, Ca, B, Zn, and Mn were also significant (Table 2).

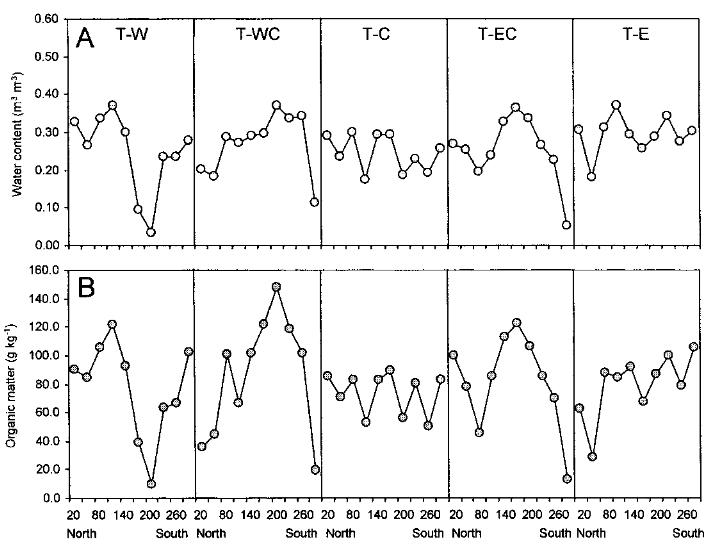

Fig. 6. Soil water content (A), and organic matter content (B) on the west transect (T-W), west-center transect (T-WC), center transect (T-C), east-center transect (T-EC), east transect (T-E).

Discussion

Soil property heterogeneity commonly occurs in cultivated soils, and the periodically flooded soil at this study site was no exception. As a poorly drained soil, the soil water content was as high as 40% and soil organic matter was as high as 16%. The soils in this grove are highly organic because the area is naturally poorly drained. The low sand content (530 mg·kg^{-1} on average) could explain the poor soil drainage (high SWC).

Significant correlations of DRW abundance with soil Mg and Ca in the present study indicate a potentially important association. Historically, soil liming has been practiced in this grove on an annual basis, and dolomite was applied at a rate of 7.4 ton·ha^{-1} across the grove in the spring of 2002. However, soil pH remained low (pH 4.9 ± 0.4), perhaps because of high rainfall (1380 mm·year^{-1}, and generally acid) and the anaerobic condition of the poorly drained soil. Since soil pH was uniform in the field (CV = 8.2%, Table 1), DRW distribution frequency was not correlated to soil pH ($r = -0.19$, Table 2). The variability and influence of soil Ca and Mg on DRW distribution frequency might be related to various factors including liming practices, the nature of the soil, site elevation, soil flooding history, soil erosion by rain and water, and Ca and Mg uptake capacity of the trees.

Overall, there was no correlation between DRW abundance and tree health at particular Tedders trap locations in the present study perhaps because relatively few trees were included in the correlation, because root weevils are only one of several factors contributing to tree decline, or because root weevils captured in Tedders traps are derived from a broader area than the specific tree under which the trap is located. In general, DRW abundance was highest in the southwestern portion of the grove, an area of relatively high elevation, with a high density of moderately and severely declined trees, and which is least susceptible to flooding, associations which might give rise to many of the other correlations in this study. Sustained flooding can be an important mortality factor for DRW larvae and has been suggested as a possible control tactic for DRW in sugarcane fields (Shapiro et al., 1997).

The DRW temporal distribution pattern observed in the present study was characterized by a distinct spring peak (June) and was probably related to seasonal variation in precipitation, and air and soil temperatures. McCoy et al. (2003), working in the same grove, reported that DRW adult emergence was highest in the spring of 2000 and 2001 when soil temperature averaged 22-24 °C, and soil water potential decreased to 3-5 centibars at a depth of 0.15-0.30 m. Nonetheless, in previous years, Tedders traps indicated that DRW population peaks in this grove occurred in the spring and the fall, and that the fall peak was larger (McCoy et al., 2003). It is unclear what factors might have contributed to the different temporal pattern of abundance observed in the present study but this pattern is similar to that reported for other groves in Florida where adult populations have been monitored with Tedders traps (Duncan et al., 2001; Stansly et al., 1997).

The *Diaprepes* male:female ratio of 2:1 observed in the present study differs from those reported in previous field studies but is similar to that observed in Tedders traps at this site during previous years (2000, male:female ratio = 1.48:1, n = 3103 adults; 2001, male:female ratio = 1.73:1, n = 5951 adults; McCoy and Stuart, unpublished). Beavers and Selhime (1976) reported male:female ratios of 0.8:1 and 0.7:1 for a citrus grove sampled in two consecutive years; Stansly et al.

Table 2. Linear correlations of *Diaprepes* abundance, tree rating and soil physico-chemical properties as defined in the text.

	Diap†	Tree Rating	WTD	SWC†	Sand	Clay	pH	SOM†	CEC†	EC†	P	K	Mg	Ca	B	Zn	Mn	Fe	Cu	H
Pearson correlation coefficients																				
Diap	1																			
Tree Rating	-0.14	1																		
WTD	-0.03	-0.04	1																	
SWC	-0.21	-0.15	0.19	1																
Sand	0.14	0.17	-0.08	-0.32*	1															
Clay	-0.11	-0.16	0.08	0.31*	-0.97**	1														
pH	-0.19	0.16	-0.18	-0.40**	0.21	-0.27*	1													
SOM	-0.12	-0.06	0.17	0.90**	-0.23	0.25*	-0.46**	1												
CEC	-0.25*	-0.03	0.13	0.79**	-0.09	0.06	-0.08	0.80**	1											
EC	-0.14	0.013	0.14	0.47**	-0.15	0.13	0.075	0.48**	0.59**	1										
P	0.04	0.18	-0.08	-0.02	0.17	-0.19	0.22	0.03	0.16	0.49**	1									
K	-0.06	0.20	0.14	0.37**	0.11	-0.10	0.17	0.41**	0.47**	0.47**	0.45**	1								
Mg	-0.31*	-0.04	0.13	0.53**	-0.12	0.07	0.14	0.46**	0.79**	0.48**	-0.04	0.37**	1							
Ca	-0.26*	0.04	0.07	0.55**	0.04	-0.09	0.31*	0.55**	0.90**	0.61**	0.24	0.51**	0.77**	1						
B	-0.13	0.12	-0.06	0.27*	0.23	-0.25*	0.33**	0.34**	0.60**	0.48**	0.47**	0.57**	0.33*	0.78**	1					
Zn	0.04	0.2	-0.06	0.06	0.28*	-0.27*	0.29*	0.2	0.34**	0.39**	0.52**	0.54**	0.04	0.54**	0.90**	1				
Mn	0.15	0.02	0.16	0.17	0.12	-0.06	-0.51**	0.26*	0.06	0.21	0.47**	0.22 ns	-0.13	-0.16	0.01	0.11	1			
Fe	0.14	-0.42**	-0.27*	-0.16	-0.05	0.08	-0.18	-0.29*	-0.29*	-0.38**	-0.33*	-0.59**	-0.28*	-0.32*	-0.25*	-0.25*	-0.07	1		
Cu	0.08	0.03	0.04	0.06	-0.11	0.12	0.07	0.06	0.11	0.02	0.41**	0.25*	0.04	0.07	0.19	0.19	0.26*	-0.12	1	
H	0.26*	0.12	0.11	-0.02	-0.04	0.12	-0.78**	0.05	-0.38**	-0.31*	-0.15	-0.31*	-0.62**	-0.68**	-0.48**	-0.28*	0.50**	0.24	-0.11	1

†Diap: Diaprepes; WTD, water table depth; SWC, soil gravimetric water content; SOM, soil organic matter content; CEC, Cation exchange capacity; EC, electrical conductivity.
*P = 0.05; **P = 0.01.

(1997) reported a ratio of 0.91:1; and Nigg et al. (2001) reported a ratio of 1.2:1. Different sampling methods and seasonal variability might explain the variation in these results.

The DRW is a serious pest and a particularly challenging obstacle to the continued profitability of the Florida citrus industry. Only a few practical control methods are available to growers despite efforts to find a control since the discovery of DRW in Florida in 1964 (McCoy et al., 2003; Stuart et al., 2003). The results of the present study suggest that soil liming, site elevation, soil flooding history, and rain or water erosion might be important factors influencing DRW distribution within groves but further study at this and other sites is necessary to confirm these relationships.

Conclusions

Diaprepes root weevil distribution varied with space and time. The southwestern portion of the grove was the high density area of trapped DRW adults, and June was the most active month for DRW during the year. The DRW distribution frequency was not related to tree health at specific trap locations but was significantly and negatively correlated to soil Mg, Ca, CEC and H. Soil liming, soil flooding history, site elevation, and rain or water erosion could be factors influencing DRW distribution but further study is necessary to test these hypotheses. More precise DRW trap monitoring and soil sampling are needed to capture more DRW and soil variability in space and time for improved DRW-soil-plant management. To achieve this goal, we recommend establishing a monitoring network using transects with trap-soil neighboring sample points located about 10 m apart.

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