

SOIL AND *DIAPREPES ABBREVIATUS* ROOT WEEVIL SPATIAL VARIABILITY IN A POORLY DRAINED CITRUS GROVE

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Soil and water variability in space and time could be important for management of the citrus root weevil, *Diaprepes abbreviatus* (L.). We conducted a study of soil, tree, and root weevil relationships in a poorly drained grove of Hamlin orange on Swingle citrumelo rootstock (*Citrus paradisi* Macfad. x *Poncirus trifoliata* (L) Raf.) in central Florida in 2002. We hypothesized that spatial soil and water variability might influence tree health and root weevil patterns. The objectives were to assess the spatial variability of soil, water, tree health, and *Diaprepes* root weevil (DRW) and to determine DRW management zones based on spatial correlations. Adult weevils were monitored using Tedders traps arranged in a 34 × 25-m grid across the grove. Soil electrical conductivity (EC) was assessed using EM38, and water table, soil texture, water content, organic matter, pH, P, K, Ca, Mg, B, Zn, Mn, Fe, and Cu were measured at each trap. The weevil population peaked in June ($P < 0.001$), and weevil density was high in areas that were low in Mg and Ca concentrations ($P < 0.05$). Semivariograms, a spatial structure function, for DRW, Mg, Ca, and EC, ranged within 75 to 100 m, which matched the limits of DRW management zones delineated using DRW and EC underlying patterns. Soil EC, Mg, Ca, and Fe were correlated, and tree decline was associated with high levels of Fe and soil flooding because plants were more water stressed in flooded areas than in non-flooded areas ($P < 0.01$). We suggest that a management unit approach might be an option for DRW control, and that flooding events and soil Fe, Mg and Ca levels might be related to tree decline and DRW distribution patterns. (Soil Science 2004; 169:650-662)

Key words: Poorly drained soil, *Diaprepes* root weevil, flooding, calcium, magnesium, citrus management zone. Variability, citrus grove, patterns.

FLORIDA citrus soils range from well-drained Entisols on relatively high, rolling landscapes to poorly drained Alfisols and Spodosols on low-lying flatwoods (Obreza and Collins, 2002). The root weevil *Diaprepes abbreviatus* (L.) (Coleoptera: Curculionidae), originally native to the Caribbean, has become a major citrus pest in Florida (Duncan et al., 2001; Nigg et al., 2001, 2003; McCoy et al., 2003; Stuart et al., 2003). *Diaprepes*

root weevil (DRW) adults feed on the leaves of all citrus varieties and deposit egg masses glued between the leaves in the citrus canopy (Duncan et al., 2001; McCoy et al., 2003; Stuart et al., 2003). Hatching neonates fall to the soil, feed on tree roots, and subsequently pupate (Nigg et al., 2001; McCoy et al., 2003; Stuart et al., 2003). *Diaprepes* larvae consumed from 3–12% (Li et al., 2003a) to 20–80% (Rogers et al., 2000) of citrus seedling roots within 6 weeks of infestation in the greenhouse. However, for mature citrus trees, symptoms of an infestation are not apparent until extensive damage from larval feeding has occurred (Nigg et al., 2001; Stuart et al., 2003). Lack of early detection and management tools can cause infested trees to decline to an unpro-

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ductive state within 5 to 7 years of an initial infestation (Nigg et al., 2001).

Since most life stages, including larvae, pupae, and teneral adults, occur in soil (McCoy et al., 2003; Nigg et al., 2003), DRW spatial patterns could be directly or indirectly influenced by characteristics of the soil and the trees on which they feed. Adult weevils might be more attracted to bigger, healthier, fuller trees for feeding and egg laying (Nigg et al., 2003) and, therefore, might be more abundant where soil physical and chemical conditions are most suitable for tree growth. Numerous properties influence the suitability of soil as a medium for plant growth (Kitchen et al., 2003), but no previous studies have quantified the effects of soil and tree conditions on DRW distribution patterns in Florida citrus (Li et al., 2003b). Soil texture was recently reported as a cause of variation in DRW larval control by entomopathogenic nematodes (Duncan, 2003), and DRW adult emergence from soil was correlated with soil temperature and moisture (McCoy et al., 2003).

Insect movement patterns are often critical to pest management strategies. Nigg et al. (2001) reported that DRW adults might move relatively little in citrus groves because 40% of recaptured marked DRW adults were found within 0–24 m of a release point over a period of 10 weeks. However, there is a need for more information about the movement and dispersal of DRW adults (Nigg et al., 2001), and the relationships between soil and water variability and DRW distribution patterns are little known (Li et al., 2003b). The distribution of DRW adults seemed to be related to concentrations of major soil chemical properties such as Mg and Ca (Li et al., 2003b), but it is not clear whether soil drainage, site elevation and flooding events influence DRW distribution patterns in the humid, acid, and warm soil environment found in Florida.

Soil waterlogging is a chronic problem that causes plant flooding stress in poorly drained soils in Florida flatwoods citrus (Boman and Obreza, 2002), and citrus rootstocks vary in their responses to flooded soil conditions (Syvertsen et al., 1983). Citrus leaf hydraulic conductivity and stomatal conductance were reduced significantly under flooded anaerobic conditions (Syvertsen et al., 1983; Li et al., 2003a). *Diaprepes* larval survival was limited under flooding conditions (Shapiro et al., 1997), but flooded citrus seedling roots were significantly more susceptible to feeding injury by DRW larvae in the greenhouse (Li et al., 2003a). Soil nutrient, pH, water, disease, and in-

sect underlying processes could be both variable and associated in space and time (Ahuja and Nielson, 1990; Klironomos et al., 1999; Nelson et al., 1999; Cassel et al., 2000; Li et al., 2002a and b). Because root waterlogging and larval feeding occur underground, the identification of specific underground infestation sites for root weevils might reduce the area to treat and could contribute to reduced treatment costs for chemical and biological control.

Soil nutrients influence citrus tree canopy performance (Alva and Tucker, 1999) and soil organism cycles (Klironomos et al., 1999). No single measurement describes adequately the influence of the soil environment on plant rooting (Kitchen et al., 2003). We hypothesized that if DRW adults tend to remain relatively close to where they emerge from the soil, then the spatial patterns of a DRW population might be related to spatial variability in tree health and to soil and water variables that may influence the performance of trees on which the weevils feed. We also evaluated the degree of plant physical stress from soil flooding events by measuring plant leaf stomatal conductance (g_s) and plant water potential (p_s) to determine whether poor drainage and soil flooding could also be associated with tree decline in the humid environment.

Delineating DRW management zones, mapping soil-flooding factors related to tree decline, and quantifying spatial correlation ranges of soil, water, and DRW variables have not been attempted in previous studies in Florida. The objectives of the present study were to (i) assess DRW distribution patterns and soil physical and chemical characteristics, (ii) delineate soil and DRW distribution zones, (iii) measure and map soil flooding factors affecting plant water stress, and (iv) determine spatial correlation functions for soil and DRW variables. This information could be useful for DRW management by zone characteristics at the field scale.

MATERIALS AND METHODS

Study Site Description

This study was a part of a project addressing seasonal distributions of life stages of *Diaprepes* root weevils in Central Florida that was begun in 2002. The study site is a citrus grove of Hamlin orange (*Citrus sinensis* (L.) Osb.) on Swingle citrumelo rootstock (*Citrus paradisi* Macfad. x *Poncirus trifoliata* (L.) Raf.) near Poinciana, Osceola County, Florida (28°22'N, 81°58'W). The 9.5-ha study area slopes between 1 and 3%, and the dif-

ference in elevation is up to 2 m. The soils, classified as Siliceous, Hyperthermic, Arenic Argiaquolls Alfisols (Soil Conservation Service, 1979), consist of sand muck over clayey materials. Across the study area are found three soil types (Fig. 1): Floridana fine sand, which covers 80% of the study area; Pineda fine sand, 19%; and Kaliga muck, 1% (Soil Conservation Service, 1979). These soils were formed in the flatwoods in sandy marine sediments at the edges of Lake Tohopekaliga. Low elevation areas of the grove were flooded after periods of heavy rain in Dec. 2002–Jan. 2003.

The grove is made up predominantly of 20-year-old orange trees, planted in two-row beds, with drainage ditches 17 m apart between the beds. There are 1409 mature trees, 758 young rootstocks (replanted in 2000), 64 gaps where trees have been removed (for determination of larval life cycle), and 13 reset trees in the study area (Fig. 1). The mature trees have been damaged by adult DRW feeding on leaves and larval feeding on roots over the last 10 years. In the grove, neonates dropping from the tree canopy averaged 370 and 940 per m² of soil surface in 2000 and 2001, respectively (McCoy et al., 2003;

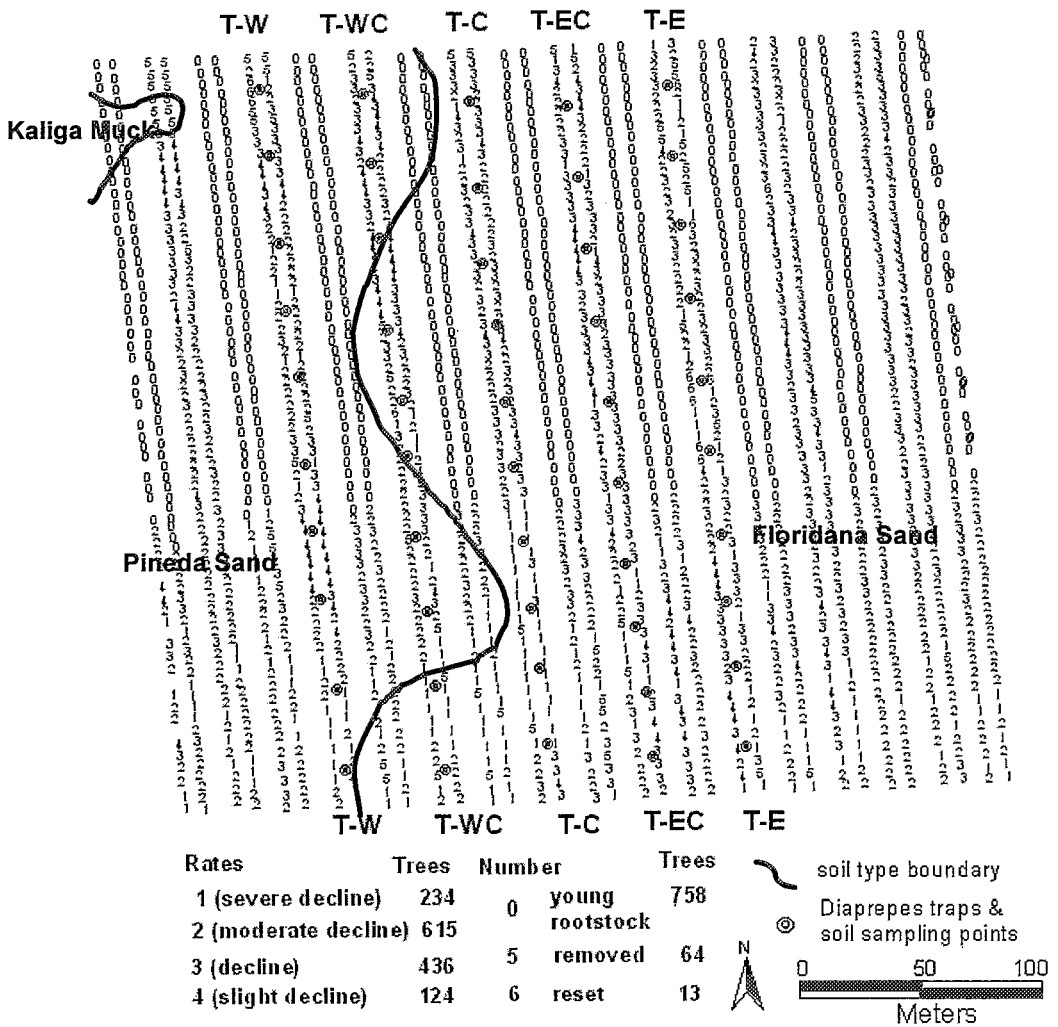


Fig. 1. Map of the study site with soil types, tree locations, tree health ratings, Tedders traps and soil sampling points, and transects, including the west transect (T-W), west-center transect (T-WC), center transect (T-C), east-center transect (T-EC), and east transect (T-E).

Nigg et al., 2003). The soil under the trees has been shown to contain an average of more than 50 DRW larvae per m^3 of fresh soil, based on tree removal and sieve sampling around the central root area ($n = 60$ trees, (McCoy et al., 2003)).

Tree and Adult Weevil Assessments

Based on the characteristics of citrus tree decline symptoms described by Tucker and Singh (1999), tree health was rated for all mature trees by visual assessment using a numerical 1 to 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 green). The classified trees were geo-referenced using a Garmin handheld GPS12 system (Garmin International, Olathe, KS).

Diaprepes adults were monitored weekly using modified pyramidal Tedders traps as described in Tedders and Wood (1994), Duncan et al. (2001), and McCoy et al. (2003). The *Diaprepes* adult population was monitored using 50 Tedders traps, placed near tree trunks 25 m apart in five 10-trap transects in a 34×25 -m grid pattern along five mature tree beds (Fig. 1). Trap geo-

positions were determined using the Garmin GPS12 system. The 10-trap transects were 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) across the study area (Fig. 1). Adult weevils were counted weekly at each trap from March to October (32 weeks). All trapped adults were identified as male or female.

During the study period, mature trees received no chemical treatments for pest control. Each year, trees received regular grove care, including liming ($CaCO_3$ at 12.3 Mg ha^{-1}), irrigation (microsprinkler at regional rate), fertilization (standard citrus mixture of 10-2-10 (N-P-K) at the rate of 0.72 kg per tree with 4 equal applications or 0.18 kg per tree each time), and regular herbicide (glyphosate at regional rate) weed control.

Elevation, Plant Leaf Water Stress, and Soil Property Assessments

Site elevation was measured using a Trimble survey grade model 4700 dual channel RTK system (Sunnyvale, CA). Plant leaf water potential (P_s) was determined using a PMS (Plant Moisture Stress) Pump-up Chamber (PMS Instrument, Corvallis, OR). Plant leaf stomatal conductance (g_s) was measured using a Delta-T porometer (Delta-T Devices, Cambridge, UK). Both leaf water stress variables were measured on young trees in the flooded and non-flooded areas after soil flooding occurred for a period of 3 weeks during Dec. 2002-Jan. 2003.

Soil EC, a measure of soil conductance and

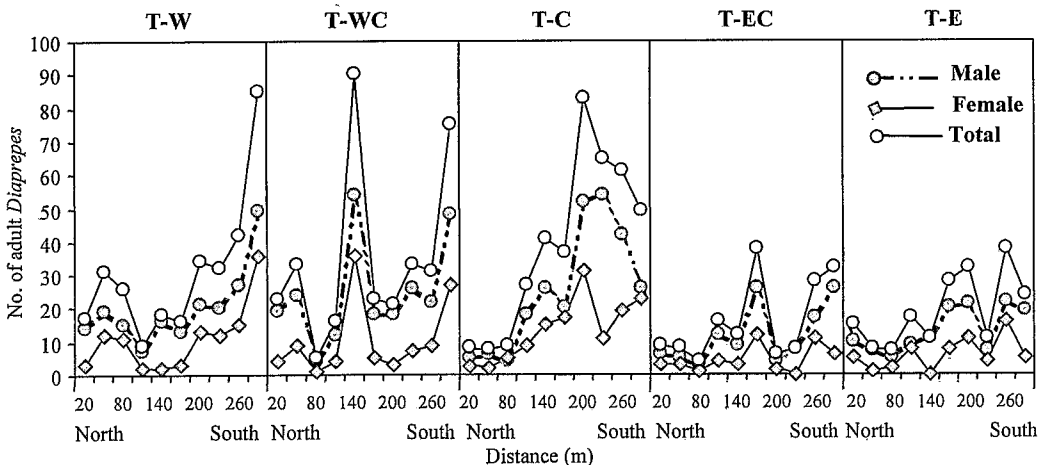


Fig. 2. *Diaprepes* root weevil distribution along the west transect (T-W), west-center transect (T-WC), center transect (T-C), east-center transect (T-EC), and east transect (T-E) across the grove measured in 2002.

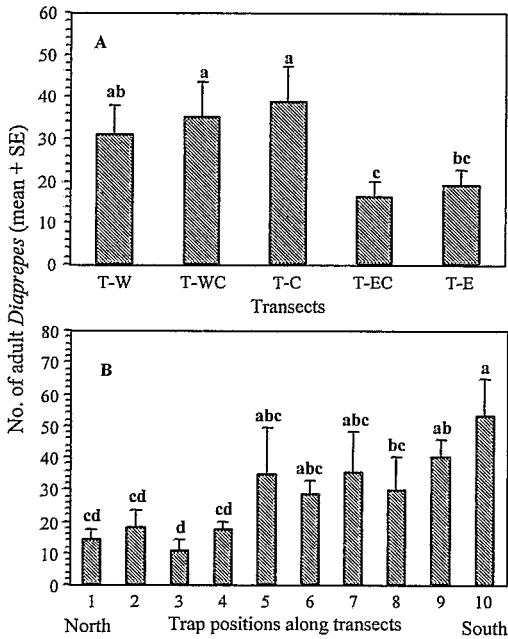


Fig. 3. Comparison of *Diaprepes* root weevil distribution within transects (A), and among trap locations (B). Bars with common letters are not significantly different ($P < 0.05$, ANOVA LSD tests).

one of the most frequently used soil variables in precision agriculture (Kitchen et al., 2003), was determined in June 2002 using an EM38 unit (Geonics, Mississauga, Ontario, Canada) in each bed across the entire field (9.5 ha). The EM38 uses electromagnetic induction as a noninvasive method to determine soil EC at two depths, 0–0.75 m and 0–1.5 m. The EM38 unit was integrated with a global positioning system (GPS) to create a geo-referenced EC map.

Soils were sampled using an 8-cm diameter hand probe at each Tedders trap site at the end of October 2002 (Fig. 1). A composite soil sample was taken from the surface to 1.2 m in 0.3-m increments. Soil water table level was measured at the time of soil sampling, based on depth of soil water saturation (Boman and Obreza, 2002). Soil samples were air dried. For the top soil (0–0.3 m), we determined soil gravimetric water content (SWC), soil organic matter (SOM) by combustion (Horwitz, 2000), sand, clay, silt, pH-H₂O (m/v 1:1), 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-H₂O. Soil texture was determined using the hydrometer method, and the Mehlich I extracted

cations and anions (P, K, Mg, Ca, B, Zn, Mn, Fe, and Cu) were analyzed using an inductively coupled argon plasma emission spectrophotometer (Waters Agricultural Laboratories, Camilla, GA) (Horwitz, 2000).

Descriptive statistics, ANOVA, and correlation analysis were conducted using PROC UNIVARIATE, PROC ANOVA, and PROC CORR (SAS Institute, 1990), respectively. PROC VARIOGRAM (SAS Institute, 1996) was used to quantify the semivariogram for soil and DRW variables. Tree, soil, and weevil mapping was done using Arcview GIS 3.2 (ESRI Inc, Redlands, CA).

RESULTS

Spatial and Temporal Distribution Patterns of Diaprepes Adult Population

A total of 16.6% of the mature trees in the grove were rated as severely declined trees (rating 1). Moderately declined (rating 2) trees represented 43.6% of the total trees, declined (rating 3) 30.9%, and slightly declined (rating 4) 8.8%. Severely and moderately declined trees were situated mainly in the southwest area of the grove, extending from the north for 120 m to the south in all transects, especially T-W, T-WC and T-C (Fig. 1).

A total of 1400 DRW adults were trapped in all five transects during the measurement period (March–Oct.). The weevil distribution was variable (CV 79%) among trap locations ($n = 50$, Table 1). Males totaled 946 (19 ± 14 weevils per trap) and females 454 (9 ± 9 weevils per trap). Sample variance was greater for males (186) than for females (78). An increase or decrease in males was generally proportional to an increase or decrease of females among monitoring traps (Fig. 2). Along transects, the weevil peaks appeared in the south (Fig. 2) where more trees were severely or moderately declined (rating 1 and 2) compared with the north (Fig. 1).

The weevil abundance had a tendency to increase from the west to the center, then decrease towards the east across the grove (Fig. 2). The weevil abundance by transect was in the order of TC > TWC > TW > TE > TEC (ANOVA, $F = 3.74$, $df = 4, 36$, $P = 0.0121$; Fig. 3A). The population frequency distribution was the most skewed, with the highest level of kurtosis among all transects on the T-W (28.3). There were significant differences in trap catches between trap positions (ANOVA, $F = 3.60$, $df = 9, 36$, $P = 0.0028$; Fig. 3B). The T-W (31 ± 21), T-WC (35 ± 27), and T-C (38.8 ± 26) were the high den-

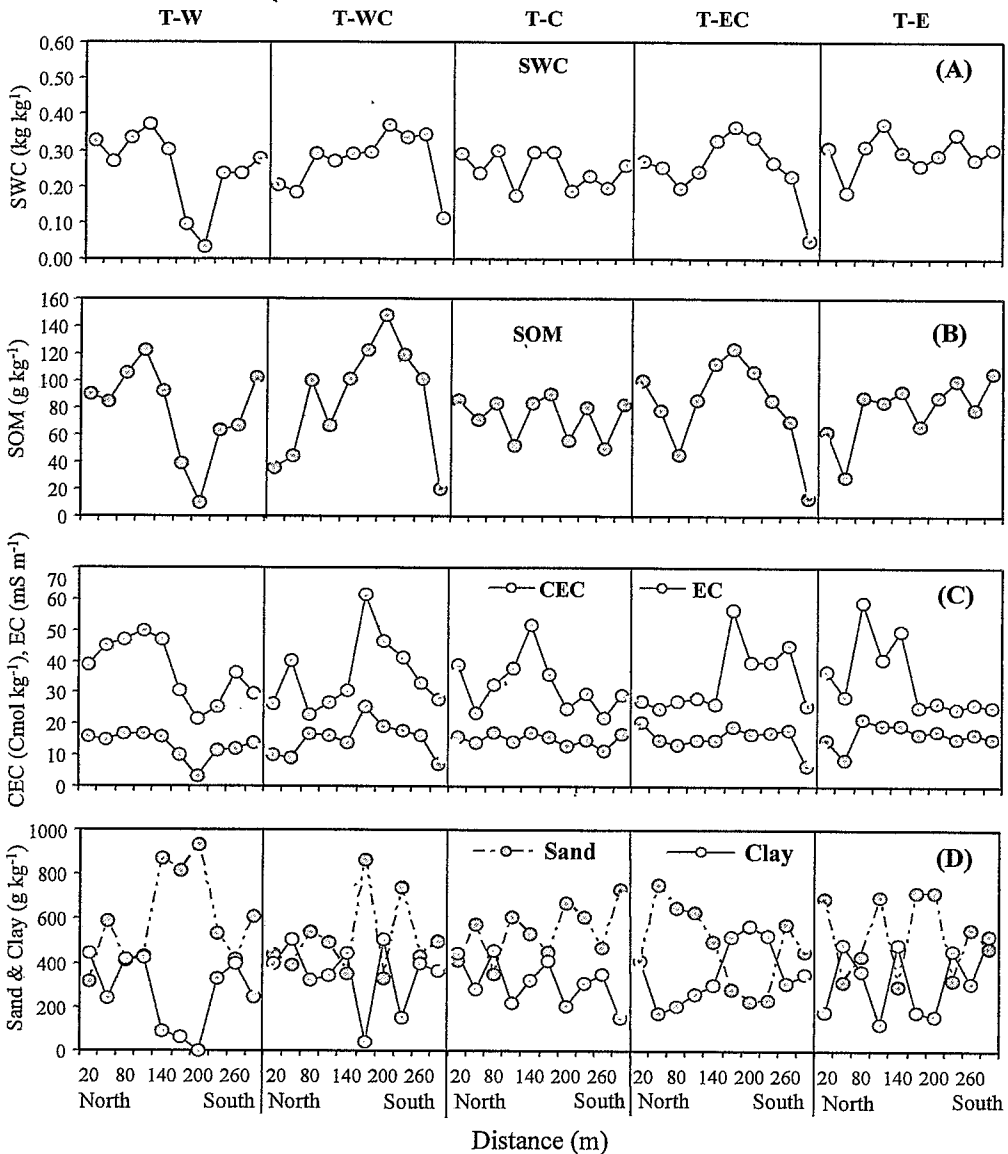


Fig. 4. Soil water content (SWC, A), soil organic matter content (SOM, B), cation exchange capacity (CEC) and electrical conductivity (EC) (C), and sand and clay content (D) on the west transect (T-W), west-center transect (T-WC), center transect (T-C), east-center transect (T-EC), and east transect (T-E). Soil variables were measured in 0–0.3 m except EC (0–0.75 m).

sity areas for DRW (76% of the total trapped weevils), and the T-EC (16 ± 12) and TE (19 ± 11) the low density areas (Fig. 2). The weevil distribution frequencies were similarly high on the T-W and T-WC (85% of the traps capturing 20–90 weevils) and similarly low on the T-EC and T-E (50% of the traps capturing 9–15 adults). The intratranssect DRW distribution frequencies are seen in Li et al. (2003b).

Temporally, weevil adults did not appear until the first week of April. The weekly peak (128 weevils) appearing in mid-June, and a smaller weekly peak (91 weevils) occurred in mid-September. The differences in weevil abundance were significant between weeks (ANOVA, $F = 7.48$, $df = 29, 1470$, $P < 0.0001$), and between months (ANOVA, $F = 12.73$, $df = 6, 343$, $P < 0.001$). The highest monthly catches occurred in

TABLE 1
Mean, standard deviation (SD) and some descriptive statistical parameters of *Diaprepes* root weevil (DRW) and soil (0–0.3 m) property variables measured in 2002 (n=50)

| Variables | Mean | SD | Min. | Max. | Skewness | Kurtosis |
|------------------------------|------|------|------|------|----------|----------|
| Diaprepes | 28 | 22 | 9.0 | 89 | 0.71 | 1.16 |
| Water table (m) | 0.9 | 0.2 | 0.6 | 1.4 | -0.47 | 0.18 |
| SWC (kg kg ⁻¹) | 0.26 | 0.08 | 0.03 | 0.37 | 1.35 | -1.11 |
| Sand (g kg ⁻¹) | 527 | 174 | 224 | 932 | -0.52 | 0.36 |
| Clay (g kg ⁻¹) | 323 | 143 | 0 | 568 | -0.69 | -0.36 |
| Silt (g kg ⁻¹) | 154 | 44 | 40 | 240 | -0.20 | -0.14 |
| pH | 4.9 | 0.4 | 4.3 | 6.2 | 1.10 | 1.12 |
| SOM (g kg ⁻¹) | 80 | 30 | 9.8 | 148 | 0.14 | -0.42 |
| CEC (Cmol kg ⁻¹) | 15 | 3.9 | 3.5 | 25 | 1.32 | -0.57 |
| EC (mS m ⁻¹) | 35 | 10 | 22 | 61 | -0.19 | 0.84 |
| BS (%) | 57 | 9.3 | 36 | 79 | -0.10 | 0.30 |
| P (mg kg ⁻¹) | 22 | 11 | 6 | 57 | 1.87 | 1.40 |
| K (mg kg ⁻¹) | 114 | 42 | 55 | 267 | 2.34 | 1.19 |
| Mg (mg kg ⁻¹) | 260 | 94 | 22 | 492 | 0.61 | -0.10 |
| Ca (mg kg ⁻¹) | 1263 | 512 | 54 | 2429 | -0.48 | -0.40 |
| B (mg kg ⁻¹) | 0.3 | 0.2 | 0.1 | 1.3 | 34.89 | 1.15 |
| Zn (mg kg ⁻¹) | 3.1 | 7 | 0.8 | 50 | 45.59 | 6.63 |
| Mn (mg kg ⁻¹) | 5.5 | 2.1 | 1.5 | 12 | 1.21 | 0.90 |
| Fe (mg kg ⁻¹) | 36 | 14 | 13 | 78 | 0.52 | 0.79 |
| Cu (mg kg ⁻¹) | 0.1 | 0.1 | 0.1 | 0.2 | 1.13 | 0.83 |
| H (%) | 43 | 9.3 | 36 | 79 | -0.10 | 0.33 |

SWC, soil water content; SOM, soil organic matter; BS, base saturation; CEC, cation exchange capacity. EC, electrical conductivity (0–0.75 m).

June (450 weevils, 9 weevils per trap), and the remaining months, except for April, had a similar level (3.1–4.7 weevils per trap). On a monthly basis, the DRW population frequency distribution was the most skewed in April (kurtosis 18.4, CV = 250%).

Spatial Patterns of Elevation and Soil Variables

The Trimble RTK-measured site elevation varied between 10.3 and 12.4 m across the field. Elevation declined in two directions (south to north, and west to east), which resulted in the north-east corner being the lowest DRW area (10.9–11.3 m, map not shown). Soil (0–0.3 m) physical and chemical characteristics were marked by a relatively low sand content (530 ± 170 g kg⁻¹) and a high SOM (80 ± 30 g kg⁻¹) across the field (Table 1) compared with the average values in citrus soils in Florida (sand 940 g kg⁻¹, SOM, 10 g kg⁻¹, Obreza and Collins, 2002). The measured water table depth (Table 1) corresponded to the soil survey data (Soil Conservation Service, 1979). Soil pH was uniform (small CV, 8%), but the value was much lower (Table 1) than the optimum soil pH for citrus production (pH 6.0–6.5, Obreza and Collins, 2002). Soil EC (0–0.75 m depth) was in the range

shown in Kitchen et al. (2003). The soil contained large amounts of exchangeable Mg, Ca, and Fe (Table 1). Among the soil parameters, Zn was the most skewed and variable with the greatest kurtosis (Table 1). Only 3 of 20 (water table depth, pH, and B) of the measured soil variables had an equal mean, median, and mode (symmetrical distribution).

Spatial patterns of SWC and SOM were comparable across the field (Fig. 4). Three similarly low areas of SWC and SOM appeared in the south on the T-W, T-WC, and T-EC (Fig. 4A,B). The soil EC (Fig. 4C) pattern was similar to the SOM (Fig. 4B), and soil CEC was proportional to the EC along the transects (Fig. 4C). Sand content showed a pattern opposite that of clay, with consistent and proportional increases and decreases along transects (Fig. 4D). The other soil variables showed patterns similar to SOM and EC (graphs not shown).

Correlations, Soil Flooding, and Plant Leaf Water Stress

The DRW population was negatively correlated with CEC, Mg, and Ca but positively correlated with H (Table 2), which indicated that the weevil density was high in areas that were low in

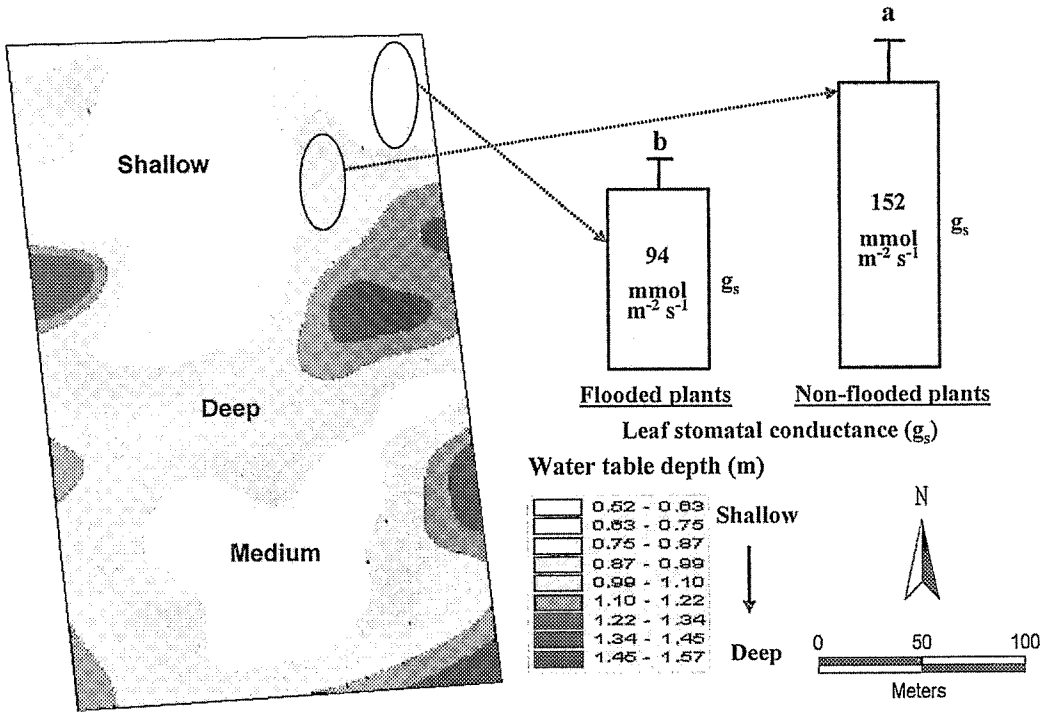


Fig. 5. Soil water table patterns measured at the time of soil sampling (Oct. 2002), and comparison of plant leaf stomatal conductance in flooded and non-flooded areas after 3 weeks of flooding.

Mg and Ca concentrations and in areas high in acidity. The weevils were situated within a soil EC range of 20 to 55 $mS\ m^{-1}$ and a large soil Mg concentration range of 10 to 500 $mg\ kg^{-1}$. Plots of DRW adults against soil Ca, Mg, and EC showed skewed distributions (towards smaller

values) similar to those of the soil hydraulic variables shown in Ahuja and Nielson (1990).

The weevil population was not correlated with tree rating at particular Tedders trap locations (Table 2), which suggests that tree canopy decline might be a consequence of weevil damage from

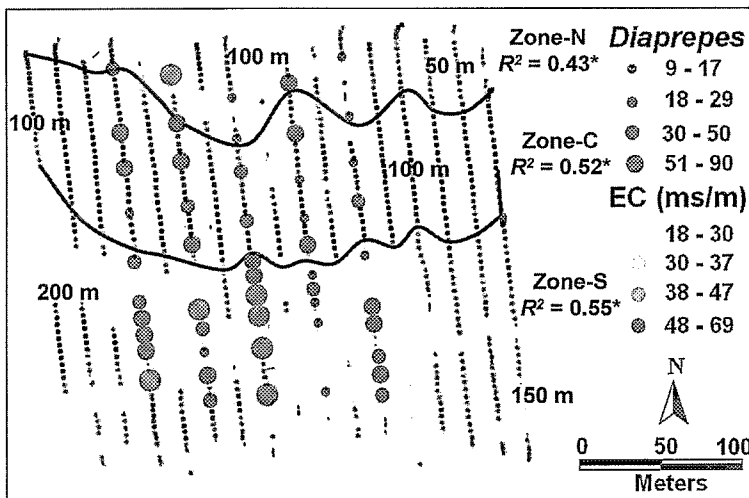


Fig. 6. *Diaprepes* root weevil distribution zoning related to soil EC patterns. *Significant at $P < 0.05$.

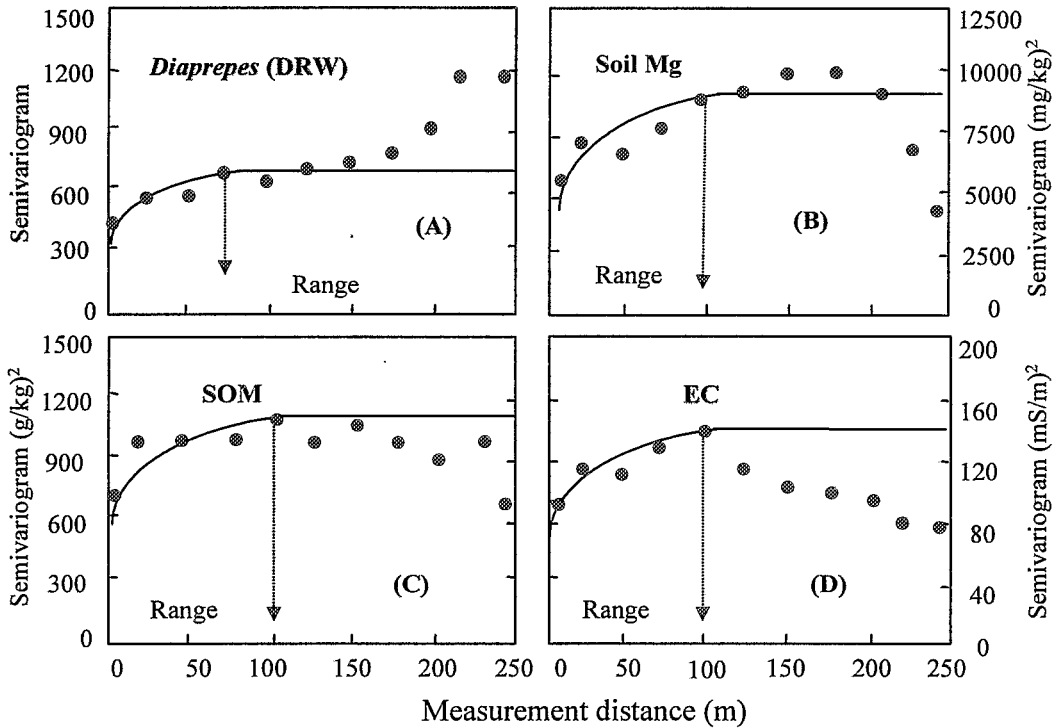


Fig. 7. Semivariograms and spatial correlation ranges of *Diaprepes* root weevil (DRW, A), soil Mg (B), soil organic matter (SOM, C), and electrical conductivity (EC, D).

previous years or that other biological, environmental, and cultural variables might be involved. The tree rating was negatively correlated with soil Fe (Table 2), and Fe was negatively correlated with water table depth ($r = -0.38, P < 0.01$). Soil water content was negatively correlated with sand and positively correlated with SOM, EC, K, Mg, and Ca (Table 2).

Water table depth, a component for distinguishing the soil saturated and unsaturated zones, varied between 0.6 and 1.4 m across the field (Table 1). Water table depth could also be delineated into north, center, and south zones as shallow, deep, and medium, respectively (Fig. 5). During Dec. 2002–Jan. 2003, soil in the north-east (NE) corner of the shallow area (water table depth 0.6 ± 0.2 m in Oct. 2002, Fig. 5) was flooded for a period of 3 weeks. Leaf stomatal conductance (g) of mature leaves from the top of young trees measured in this flooded area varied from 20 to 248 $\text{mmol m}^{-2}\text{s}^{-1}$ (94 ± 63 , three leaves per tree, $n = 48$ readings), which was significantly lower ($P < 0.001$) than the g values of 46–325 $\text{mmol m}^{-2}\text{s}^{-1}$ (152 ± 85 , three leaves per tree, $n = 48$ readings) measured in the non-flooded area (Fig. 5), which was the deep soil wa-

ter table zone (1.2 ± 0.2 m in Oct. 2002). However, leaf water potential P_a did not differ among trees in the flooded areas (0.66 ± 0.18 MPa, $n = 12$) versus the non-flooded areas (0.66 ± 0.10 MPa, $n = 12$).

Management Zoning and Spatial Correlation Ranges for Soil and Weevil Variables

Using soil EC spatial pattern as a zoning reference, three management zones, defined as north (Zone-N), center (Zone-C), and south (Zone-S), were delineated for the DRW adult population (Fig. 6). In zone-N, there were few traps ($n = 6$), and both soil EC assessments (34.7 ± 6.2 mS m^{-1}) and weevils (28.8 ± 27.9) were at medium levels. Compared with Zone-N, Zone-C was higher in soil EC (43.5 ± 6.0 mS m^{-1}) and lower in weevils (20.8 ± 14.7 , $n = 16$ traps). Zone-S was lower in soil EC (28.1 ± 5.4 mS m^{-1}) and higher in weevils (39.1 ± 25 , $n = 28$ traps). As a result, correlations between soil EC and DRW counts were significant for individual zones (Fig. 6).

The semivariograms for DRW and soil variables showed similar patterns within a distance of 75 to 100 m (Fig. 7). The semivariogram for

DRW was low within a distance of 75 m but increased with distance to stabilize at a distance of 200 m (Fig. 7A). Soil Mg had a low semivariogram within a distance of 100 m, decreasing from a distance of 150 m (Fig. 7B). The range of spatial correlation for adult weevils was up to 75 m (Fig. 7A) and was 100 m for soil Mg (Fig. 7B). The semivariogram for SOM and EC showed a decreasing trend from the peak point at 100 m (Fig. 7C,D). As a result, DRW, Mg, SOM, and EC were spatially correlated within a distance of 75 to 100 m (Fig. 7). The other soil variables (pH, CEC, sand, K, and Ca) were also spatially structured, with a range of 50 to 100 m (semivariograms not shown).

DISCUSSION

Diaprepes Distribution Pattern and Soil Heterogeneity

The correlations between DRW distribution and soil variables (Table 2) suggest that the root weevils captured in Tedders traps might emerge in, be attracted to, or be arrested in areas with particular characteristics. In central Florida, Nigg et al. (2001) reported that marked DRW adults tend to stay relatively close to where they were released in citrus groves. During a 10-week period, 40% of the marked weevils were recaptured within 0 to 24 m of a release point, and a further 41% were recaptured within 25 to 72 m (Nigg et al., 2001). Thus, weevils could be associated with a fairly limited area relative to our soil sampling distances (25 m between traps) along transects.

The soil and DRW variables in the grove were spatially structured (Fig. 7). Belowground soil water, pH, SOM, N, P, Mg, and Ca (Klironomos et al., 1999; Li et al., 2002a and b) and microbial biomass, bacteria, and nematode variables (Klironomos et al., 1999) were not random. In the entire field, the root weevil distribution was not related to total soil solute based on the low correlation between soil EC and DRW (Table 2). However, management zoning for DRW encompassed the delineation of soil EC patterns into zones, which were broadly homogeneous with respect to the DRW distribution and were also relatively uniform with respect to soil characteristic EC (Fig. 6). Therefore, the DRW and soil EC variables are related in individual zones (Fig. 6), and, as a result, these zones can be used as DRW-tree-soil management units.

It is important to note that the size of the determined DRW management zones (Fig. 6) matched the spatial correlation ranges for DRW,

EC, Mg, and SOM based on their semivariograms (Fig. 7). The zone limits from north to south along the row varied between 50 and 100 m in zone-N, 100 to 120 m in zone-C, and 150 to 200 m in zone-S (Fig. 6). Similarly, the semivariogram analysis showed that these soil and weevil variables had a low and similar semivariance within a distance of 75 to 100 m (Fig. 7), whereas the other soil properties (pH, CEC, sand, and K) were spatially dependent within 50 to 100 m, close to the management zone limits (Fig. 6). The determined semivariogram ranges could be used as pest-tree-soil measurement units. Similar suggestions have been made in studies in other areas (Ahuja and Nielsen, 1990; Klironomos et al., 1999; Nelson et al., 1999; Cassel et al., 2000; Li et al., 2002b).

Elevation, Soil, and Flooding Features Related to Diaprepes Distribution Patterns

The SWC was as high as 0.40 kg kg⁻¹ in this poorly drained soil, and SOM was as high as 160 g kg⁻¹ (Table 1). The soil is highly organic because the area is poorly drained. The low sand content (530 mg kg⁻¹ on average) probably explains the poor soil drainage (high SWC) leading to partial soil flooding during the rainy season. In addition, soil flooding in some parts of the grove, but not in others, was probably caused by differences in elevation. Inasmuch as the weevils were more abundant in the south of the grove (Fig. 2), the non-flooded high elevation area (Fig. 5), the root weevils may have emerged in greater numbers from the non-flooded (or high elevation) soil. Sustained flooding could be an important mortality factor for DRW larvae and has been suggested as a possible control tactic for DRW (Shapiro et al., 1997).

Flooding events (or water erosion) may also have contributed to tree decline. The drainage condition was the same (ditch network) throughout the entire grove, and the raised soil beds were established to create an unsaturated soil volume for root growth. However, soil flooding could occur in the NE corner, a shallow water table and low elevation area (Fig. 5). A shallow water table is detrimental to tree health (Boman and Obreza, 2002), and the plants were significantly more water stressed in flooded areas than in non-flooded areas (Fig. 5). Flooding of the root zone could lead to anaerobic conditions and could affect many plant processes (Syvertsen et al., 1983). In the greenhouse, flood damaged citrus seedlings were significantly more susceptible to both water stress and DRW larval feeding injury than seed-

TABLE 2
Pearson Correlation coefficients between Diaprepes root weevil, orange tree rating, and soil physical and chemical properties in the 0-0.3-m depth

| | DRW† | Tree Rate | SWC† | Sand | Clay | Silt | pH | SOM† | CEC† | EC† | P | K | Mg | Ca | Fe | H |
|-----------|--------|-----------|---------|---------|---------|-------|---------|--------|---------|---------|--------|---------|--------|---------|------|---|
| DRW | 1 | | | | | | | | | | | | | | | |
| Tree Rate | -0.14 | 1 | | | | | | | | | | | | | | |
| SWC | -0.21 | -0.15 | 1 | | | | | | | | | | | | | |
| Sand | 0.14 | 0.17 | -0.32* | 1 | | | | | | | | | | | | |
| Clay | -0.11 | -0.16 | 0.31* | -0.97** | 1 | | | | | | | | | | | |
| Silt | -0.21 | -0.08 | 0.24 | -0.79** | 0.67** | 1 | | | | | | | | | | |
| pH | -0.19 | 0.16 | -0.40** | 0.21 | -0.27** | -0.07 | 1 | | | | | | | | | |
| SOM | -0.12 | -0.06 | 0.90** | -0.23 | 0.25* | 0.14 | -0.46* | 1 | | | | | | | | |
| CEC | -0.25* | -0.03 | 0.79** | -0.09 | 0.06 | 0.13 | -0.08 | 0.80** | 1 | | | | | | | |
| EC | -0.14 | 0.013 | 0.47** | -0.15 | 0.13 | 0.01 | 0.075 | 0.59** | 0.48** | 1 | | | | | | |
| P | 0.04 | 0.18 | -0.02 | 0.17 | -0.19 | -0.16 | 0.22 | 0.16 | 0.49** | 0.47** | 1 | | | | | |
| K | -0.06 | 0.20 | 0.37** | 0.11 | -0.10 | -0.04 | 0.17 | 0.41** | 0.48** | 0.45** | 0.37** | 1 | | | | |
| Mg | -0.31* | -0.04 | 0.53** | -0.12 | 0.07 | 0.18 | 0.14 | 0.46** | 0.79** | -0.04 | 0.51** | 0.77** | 1 | | | |
| Ca | -0.26* | 0.04 | 0.55** | 0.04 | -0.09 | 0.07 | 0.31* | 0.55** | 0.90** | 0.61** | 0.24 | 0.51** | 0.77** | 1 | | |
| Fe | 0.14 | -0.42** | -0.16 | -0.05 | 0.08 | -0.14 | -0.18 | -0.29* | -0.29* | -0.38** | -0.33* | -0.59** | -0.28* | -0.32* | 1 | |
| H | 0.26* | 0.12 | -0.02 | -0.04 | 0.12 | -0.12 | -0.78** | 0.05 | -0.38** | -0.31* | -0.15 | -0.31* | 0.62** | -0.68** | 0.24 | 1 |

Pearson correlation coefficients (r)

lings that were not flood damaged (Li et al., 2003a). Studies in other areas have suggested the influence of site elevation on soil water availability and crop yields (Li et al., 2002a). In our field, since the site elevation varies about 0.2 m within a distance of 10 to 15 m, DRW monitoring traps (also soil sampling distance) should be about 10 to 15 m apart to capture the maximum soil, DRW, and elevation variability.

The significant correlations of DRW and soil Mg and Ca (Table 2) underscore the importance of exchangeable soil Ca ($1263 \pm 512 \text{ mg kg}^{-1}$) and Mg ($260 \pm 94 \text{ mg kg}^{-1}$) concentrations that made up much of the CEC in this soil ($r = 0.90$ and 0.79 , Table 2), which was also correlated with DRW frequency (Table 2). The high levels of soil Ca and Mg in this citrus soil in Florida were similar to those measured in a wheat-soybean-corn rotation field on the Coastal Plain of North Carolina (Li et al., 2002b). High levels of soil Ca and Mg in agricultural soils in humid areas are likely associated with the need for frequent liming in order to raise soil pH. Historically, soil liming has been practiced in the grove on an annual basis, and dolomite was applied at a rate of 7.4 t ha^{-1} across the grove in the spring of 2002. However, soil pH remained low (4.9 ± 0.4 , Table 1), probably because of high rainfall (1300 mm per year, generally acid) and the anaerobic condition of the poorly drained soil. Because soil pH was uniform in the field ($\text{CV} = 8.2\%$), the DRW pattern was not correlated to soil pH (Table 2). The influence of soil Ca and Mg on DRW patterns could have been related to liming practices, drainage, soil erosion by rain and flooding, site elevation, or the fluctuating water table.

The factors discussed in the previous paragraph may have affected tree health and DRW distribution pattern, which may explain the lack of a direct correlation between DRW and tree rating variables (Table 2). Nigg et al. (2003) reported that there was no correlation between citrus tree canopy volume and the numbers of DRW neonates dropping from trees, but a significant, positive correlation was found for tree canopy diameter and DRW neonate numbers. Larger, healthier trees are likely to be good sources of food for adult DRW and might be subjected to more egg laying and more neonate drop than smaller, weaker trees. However, neonates dropping to the ground are faced with many predators and pathogens on the soil surface (e.g., ants (Stuart et al., 2003)) and belowground (e.g., nematodes, (Duncan, 2003)), which might complicate correlation patterns between the DRW population,

tree rating, and other soil variables. We suggest that correlations between the DRW adults and soil Mg and Ca levels, the relationships between plant water stress, tree decline, and flooding events, and the management zoning and semivariogram ranges derived here could be used for more effective DRW-tree-soil management.

CONCLUSIONS

Diaprepes root weevil distribution varied with space and time. The high density areas of trapped DRW adults were the non-flooded high elevation areas in the south-western grove. Early spring (June) was the peak period for DRW adult abundance and could be the optimal time for treatment applications. The DRW adult distribution pattern was significantly correlated to soil Mg, Ca, CEC, and H (acidity), which suggests an influence of soil liming practices on tree canopy status and the DRW population. Tree canopy decline was also associated with high levels of soil Fe concentration. Soil flooding events could be a factor damaging trees because plants were significantly more water stressed in flooded areas than in non-flooded areas. Site elevation and floodwater erosion could also result in soil and tree variability. The match of the semivariogram ranges for DRW and soil variables with the DRW distribution zone limits suggests management zones for DRW control. However, further study at this and other sites is needed to provide more information about the relationships between DRW and soil liming, flooding erosion, site elevation, and drainage.

ABBREVIATIONS

BS, base saturation;
 CEC, cation exchange capacity;
 EC, soil electrical conductivity;
 DRW, *Diaprepes* root weevil;
 g_s , plant leaf stomatal conductance;
 p_a , plant water potential;
 SOM, soil organic matter content;
 SWC, soil gravimetric water content;
 T-C, center transect;
 T-E, east-transect;
 T-EC, east-center transect;
 T-W, west-transect;
 T-WC, west-center transect

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