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Associations of soil iron with citrus tree decline and variability of sand, soil water, pH, magnesium and *Diaprepes abbreviatus* root weevil: Two-site study

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Abstract

The hypothesis of associations of environmental soil heterogeneity with citrus tree decline and *Diaprepes abbreviatus* (L.) root weevil variability was tested in two flatwoods fields of 'Hamlin' orange trees (*Citrus sinensis* (L.) Osb.). Studies were conducted on a loamy, poorly drained Mollisol in Osceola County, central Florida in 2002, and on a sandy, poorly drained Spodosol in DeSoto County, south-west Florida during 2001–2003. Adult weevils were monitored using 50 Tedders traps arranged in a 34 m × 25 m grid at the Osceola site, and using 100 identical traps in a 30 m × 15 m grid at the DeSoto site. Soil water content (SWC), texture, pH, Ca, Mg, Fe, Cu and other nutrients were measured at each trap. Soil was strongly acidic (pH 4.9 ± 0.4) at the Osceola site but near neutral (pH 6.6 ± 0.4) at the DeSoto site. The Mehlich-I extractable soil Mg and Ca were correlated to soil pH and SWC in both soils, and extractable Fe was related to pH, SWC and Mg in the Spodosol ($0.30 < R^2 < 0.65$, $P < 0.01$). The weevil density was high in areas low in soil Mg and Ca in the acidic Mollisol, but high in areas with high soil pH, and Mg and low sand content in the near neutral Spodosol ($P < 0.05$). Tree decline was associated with soil Fe concentrations >40 mg kg^{-1} in the Mollisol ($P < 0.01$). Weevil density was low at a soil pH between 5.7 and 6.2. The range of spatial dependence of weevil population, soil pH, SWC, Fe, Mg and sand varied between 60 and 100 m in the Mollisol and the Spodosol. Soil-weevil-tree simple and multivariate linear models were established to put into practices for predicting and controlling the weevil population and tree decline in the future. Differences in site characteristics suggested the need for site-specific weevil and citrus tree management.

Keywords: Citrus tree management; Linear regression model; Root weevil control; Soil pH; Soil texture; Soil-weevil spatial patterns

1. Introduction

Florida citrus is often grown on shallow, poorly-drained Mollisols and Spodosols in the "flatwoods" regions of the state. Although flatwoods soils are often sandy, low elevation results in poor drainage (Obreza and Collins, 2002). Most flatwoods soils contain high levels of active hydrogen because of high rainfall, aluminum from soil reacting with water to give free hydrogen, and the use of acid forming fertilizers such as NH_4NO_3 that contribute H^+ to the soil solution (Kidder, 2003). Soil pH and soil water content (SWC) are among the most important factors to citrus growth, and management of soil acidity and soil waterlogging have received much attention (Obreza and Collins, 2002; Kidder, 2003; Li et al., 2004b, 2004c).

Soil acidity, waterlogging and *Diaprepes abbreviatus* root weevil infestation can occur simultaneously in Florida citrus groves (Li et al., 2004c, 2006). The root weevil *Diaprepes abbreviatus* (L.) (Coleoptera:Curculionidae), originally from the Caribbean, has become the most injurious pest to citrus in Florida (Rogers et al., 2000; Duncan et al., 2003; McCoy et al., 2003; Nigg et al., 2003; Stuart et al., 2003). Most life stages of this root weevil including larvae, pupae and teneral adults occur in soil, and larval feeding by *Diaprepes* can break the resistance of structural roots to infection by *Phytophthora* spp. and lead to

Abbreviations: CEC, cation exchange capacity; CV, coefficient of variation; GPS, global positioning systems; LSD, least significant difference; S.D., standard deviation; SOM, soil organic matter content; SWC, soil water content; TDR, time domain reflectometry

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tree death (Duncan et al., 2003; McCoy et al., 2003; Stuart et al., 2003). Greenhouse studies conducted in Florida found that *Diaprepes* larval survival was related to soil type or soil pH under controlled greenhouse conditions (Rogers et al., 2000; Li et al., 2004c, 2006). Soil flooding resulted in citrus tree water stress; and variations of some soil macronutrients were correlated with *Diaprepes* adult distribution patterns under citrus tree canopies in the field (Li et al., 2004b).

Soil nutrients influence soil organism cycles (Klironomos et al., 1999). The soil nutrients influence tree leaf quality and the abundance of most herbivorous insects (Lower et al., 2003). Movement, survival and vertical distribution of *Cyrtomenus bergi* with time was dependant on soil moisture (Riis and Esbjerg, 1998), and the influence of insects on crop yield was greater than the influence of soil water holding on crop yield (Li et al., 2004a). Acid soils contain high levels of active hydrogen and/or aluminum in relation to Ca and Mg, and plants have a limited tolerance to low pH (Kidd and Proctor, 2001). Soil liming adds a considerable amount of Ca and Mg to the soil but too much Ca and Mg in the soil can interfere with the availability of other nutrients (Sopher and Baird, 1982; Bohn et al., 2001). Iron (Fe), a micronutrient for plant growth, decreases significantly when soil pH increases from 5 to 6 (Sopher and Baird, 1982; Bohn et al., 2001). High concentrations of Fe^{2+} in the soil solution could form a plaque to affect absorption of nutrients by roots (Liu et al., 2004).

To our knowledge, up to this date there are no studies that have examined the processes of plant environmental stresses from root weevil feeding, soil acidity, water logging, and heterogeneity of major and minornutrients in different soils. In the literature, studies are limited to address plant decline from root weevil feeding only, or from poor soil conditions only. Insect distribution was spatially structured (Williams et al., 1992; Li et al., 2004b), and soil pH, soil water content (SWC) and texture were associated with plant growth in different soils (Kidd and Proctor, 2001; Li et al., 2001, 2002). The toxicity of excess H^+ to plants examined in the greenhouse explained why plants grow poorly on very acid soils (Kidd and Proctor, 2001). However, it is not known whether low soil pH can cause an excess of soil Fe^{2+} in citrus soils, or whether soil pH, SWC and other characteristics may influence tree status and *Diaprepes* weevil distribution in citrus groves. Insect attacks on plants were not uniformly distributed (Matthiessen and Learmonth, 1993). The *Diaprepes* adult pattern was related to some soil macronutrients at one site (Li et al., 2004b), and there is a need to examine the spatial association processes of soil characteristics, trees and *Diaprepes* weevils at different sites.

We hypothesized that soil pH and SWC could cause soil macro- and micro-nutrient variability in different citrus soils, and that SWC, pH and soil nutrients could be associated with the processes of citrus tree decline and *Diaprepes* root weevil distribution patterns in different citrus groves. Our objectives were to (i) examine the spatial association processes of soil pH, SWC, macro and micronutrients, citrus tree decline, and *Diaprepes* weevil variability on Mollisols and Spodosols, and (ii) give insights of agronomic options for the tree, soil, and root weevil management based on spatial correlation. If soil pH, SWC, and nutrients were related to tree health and weevil patterns in different soils, then improvement of soil conditions based on site-specific characteristics could be an option for citrus and *Diaprepes* weevil management at the field scale.

2. Materials and methods

2.1. Description of study sites

We conducted studies of soil characteristics, plant, and *Diaprepes* root weevil relations in two fields of 'Hamlin' orange trees (*Citrus sinensis* (L.) Osb.) in Florida. One field was on a loamy Mollisol in Osceola County (28°07′40″ N, 81°21′10″ W), east of Poinciana, central Florida (USDA-NRCS, 2003). The other field was on a sandy Spodosol in DeSoto County (27°06′55″ N, 81°55′05″ W), south of Arcadia, southwest Florida (SCS, 1989).

2.1.1. Osceola site

The study was part of an ongoing project addressing life stages of *Diaprepes* root weevils since 1999. The *Diaprepes* population data before 2001 at this site were reported (McCoy et al., 2003; Nigg et al., 2003), and part of the 2002 data were also reported (Li et al., 2004b). The study site was a flatwoods citrus grove of 'Hamlin' orange trees on Swingle citrumelo rootstock (*Citrus paradisi* Macfad. × *Poncirus trifoliata* (L.) Raf.), located about 500 m in the south of Lake Tohopekaliga. Because of low elevation, flooding occurred, depending on the rain pattern each year. In 2002, a ditch was dug west to east across the grove to improve drainage. The study area was reduced to 9.5 ha and the experimental design was changed as shown in Fig. 1. In this paper, we used part of the soil and weevil data collected in 2002 from this site.

The Osceola site consisted predominantly of 20-year old orange trees in raised two-row beds with drainage furrows between the beds, 17 m apart (Fig. 1). The trees were generally in decline and had been infested by *Diaprepes* root weevil over the previous 10 years (McCoy et al., 2003). The soils, formed in the flatwoods sediments at the edges of the lake, were classified as Loamy, Siliceous, Hyperthermic Arenic Argiaquolls Mollisols (USDA-NRCS, 2003). Across the site there were three soil types: Floridana sandy loam (80% of the areas), Pineda sandy loam, and Kaliga muck, an organic soil (Fig. 1). These soils were poorly drained because the site was in a depression near the lake.

Trees at the Osceola site received regular liming, irrigation, and fertilization but no chemical treatments for pest control during the study period. Dolomite ($CaCO_3 \cdot MgCO_3$) was applied at the rate of 7.4 Mg ha^{-1} year^{-1}. Trees were irrigated at the rate of 87 L tree^{-1} h^{-1} using microsprinklers based on rain patterns. Fertilizations were at the rates of 220 N, 44 P and 220 K kg ha^{-1} with four equal applications each year using a standard citrus mixture of 10–2–10 (N–P–K). Grass under tree canopy was mowed monthly. In 2002, the air temperature averaged 25.1 °C and 0.1 m depth soil temperature averaged 29.2 °C. The total rain was 1339 mm with 61% falling in April through September, close to the 30-year average (1380 mm year^{-1} with 65%

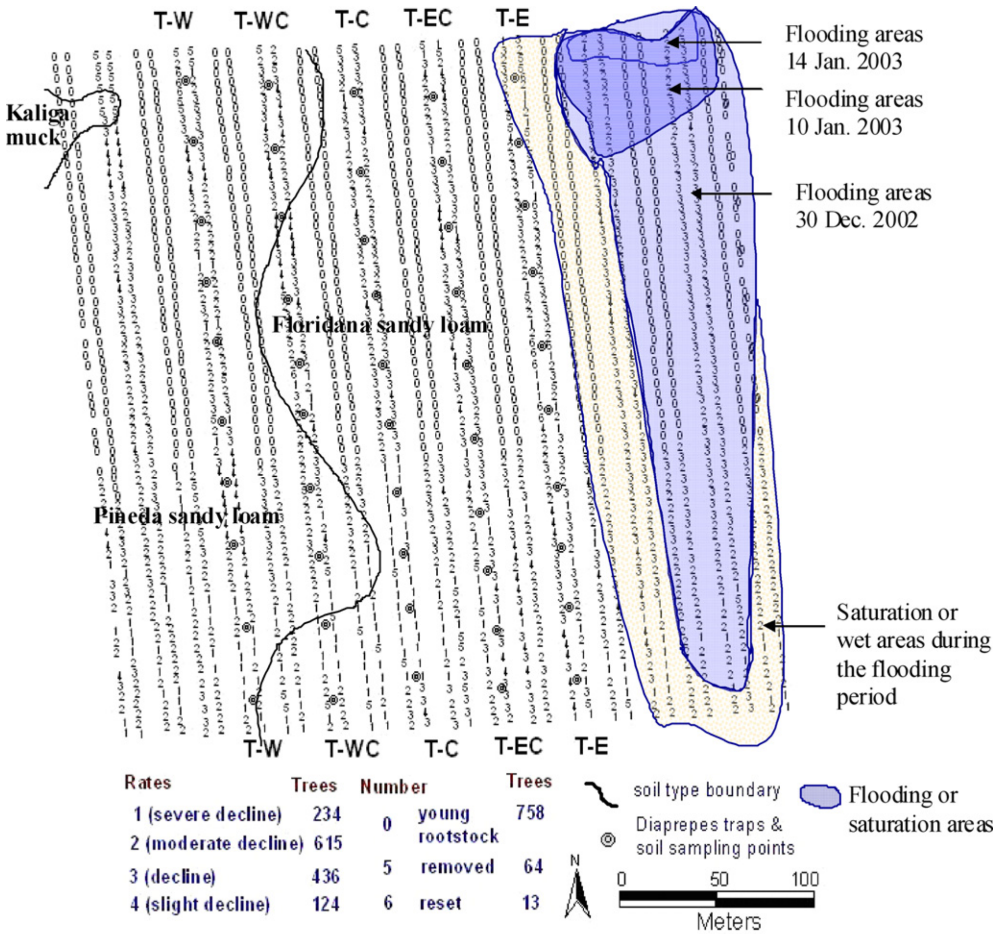

Fig. 1. Map of the Osceola study site with soil type boundary, tree, tree bed and Tedders trap locations, tree rating, and flooding areas. T, transect (tree bed); T-W, west transect; T-WC, west-center transect; T-C, center transect; T-EC, east-center transect; T-E, east transect.

during April–September). The data were obtained from Florida Automated Weather Network (FAWN, University of Florida).

2.1.2. DeSoto site

A 3-year study of *Diaprepes* adult population monitoring was conducted at this site during 2001–2003. The study site was a flatwoods citrus grove of ‘Hamlin’ orange trees on sour orange/bittersweet rootstocks (*Citrus aurantium* L.). The nearest stream, the Peace River, was about 3.5 km to the west of the site. The soils, formed in thick beds of sandy marine sediment on the Suwannee Limestone, were classified as Sandy, Siliceous, Hyperthermic Typic Haplaquods Spodosols (SCS, 1989). Across the study site there were two soil types: Ona fine sand (95%), and Smyrna fine sand on the south-east corner (Fig. 2). Because of low elevation, these sandy soils are poorly drained with moderate permeability and low water holding capacity (SCS, 1989).

Trees, planted in 1990, were in four-row beds with 3 m × 8 m tree spacing (Fig. 2). Unlike the Osceola site, a drainage furrow for evacuating surface water was only necessary for every four rows of trees, which illustrated the better drainage capacity of the soils at the DeSoto site compared to the two-row tree beds at the Osceola site. The trees have been infested by *Diaprepes* root weevils since 1997, a shorter infestation period than the Osceola site. During the study period, trees received regular grove care including irrigation, fertilization, and pest control. Irrigation and fertilization were done using the regional recommendations described for the Osceola site. No lime was applied. The pest treatment involved sprays of Sevin 80 S (Bayer Crop Science, Research Triangle Park, NC) with four uniform applications at the rate of 2.8 kg ha^{-1} each time, the minimum rate of the regional recommendation. A copper fungicide was applied to control greasy spot, citrus scab, and alternaria brown spot.

At the DeSoto site, the air temperature during the study period was 21.6–21.8 °C, close to the 30-year average, 21.7 °C (SCS, 1989). The total rain was 12–20% more than the 30-year average, 1187 mm year^{-1} (SCS, 1989) with 1340, 1422 and 1328 mm in 2001, 2002 and 2003, respectively.

2.2. Adult weevil and soil assessments

At both sites, the *Diaprepes* adult populations were monitored weekly using modified pyramidal Tedders traps as described by McCoy et al. (2003). At the Osceola site, a total of 50 Tedders traps were placed 25 m apart, near tree trunks, in five, 10-trap transects in a 34 m × 25 m grid pattern along five tree beds, running from the north to the south (Fig. 1). Trap geo-positions were determined using a Garmin GPS12 system (Garmin

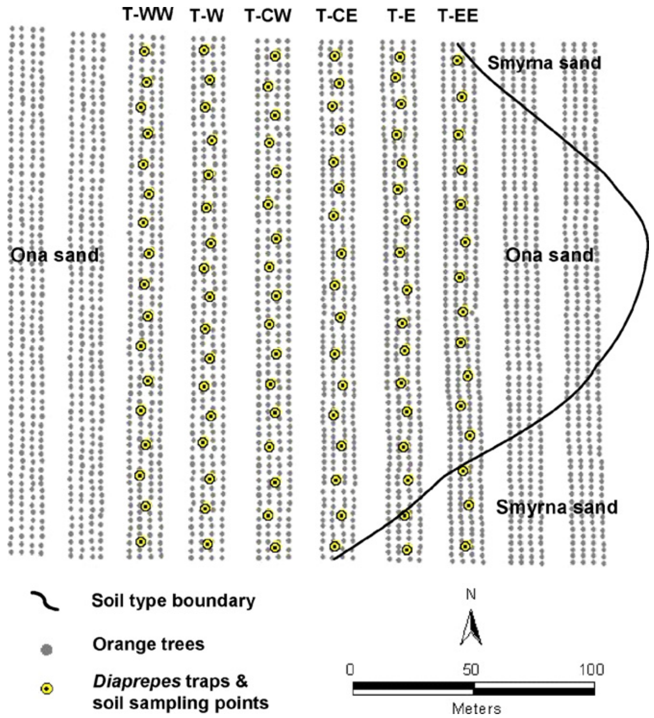

Fig. 2. Map of the DeSoto study site with soil type, tree bed, Tedders trap locations. T, transect (tree bed); T-WW, outside west transect; T-W, west transect; T-WC, west-center transect; T-EC, east-center transect; T-E, east transect; T-EE, outside west transect.

International, Olathe, KS). 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 at the Osceola site (Fig. 1). The weevils were monitored weekly from March to December in 2002. Flooding and water saturation areas were also positioned using the Garmin GPS12 system.

At the DeSoto site, a total of 100 Tedders traps were used to monitor the adult weevil population. Traps were placed 15 m apart, also near tree trunks, in the two central rows on each four-row tree bed in a 30 m × 15 m grid pattern along six tree-beds, running also from the north to the south (Fig. 2). The weevil monitoring area was 260 m × 180 m. Each transect had 17 traps except the external east transect T-EE, which had 15 traps (Fig. 2). The weevils were monitored weekly, between January and December, each year during the study period.

Soil was sampled at the Osceola site in October 2002, and at the DeSoto site in October 2003. A composite soil sample was taken at the 0–0.3 m depth at each Tedders trap. Soil samples were air dried. Monthly SWC at the 0–0.15 m depth was measured using a Scout TDR probe (Spectrum, Plainfield, IL) at the Osceola site. We determined soil (0–0.3 m) pH-H_2O (m/v, 1:1), SMP pH-buffer, gravimetric SWC with soil dried at 100 °C in the oven using the method described in Li et al. (2001), soil organic matter (SOM) by combustion (Horwitz, 2000), and texture using the hydrometer method (Gee and Bauder, 1986). The Mehlich-I extractable major and minor cations (P, K, Mg, Ca, Fe and Cu) were analyzed using an inductively coupled argon plasma emission spectrophotometer (Horwitz, 2000). Cation exchange capacity (CEC) was estimated using the equation CEC = (K/780 + Ca/400 + Mg/240) + factor, where factor = (8 − pH_{buffer}) × 8 (Horwitz, 2000). Total exchangeable hydrogen (H) was estimated using the equation H = 100% − base saturation (BS), where BS = K% + Ca% + Mg%, K% = [(K/780)/CEC] × 100, Ca% = [(Ca/400)/CEC] × 100, and Mg% = [(Mg/240)/CEC] × 100 (Horwitz, 2000).

2.3. Tree decline assessment and data statistics

At the Osceola site, tree decline was rated by visual assessment for all mature trees based on the characteristics of citrus tree decline symptoms as described by Blazquez (1991). We used a numerical 1–4 ranking system as follows: 1 = severe decline, 2 = moderate decline, 3 = decline, and 4 = slight decline. The rating 1, severely decline trees were canopy of flush only on major limbs with small leaves, and the rating 4, slightly declined trees were well-defined canopy that cannot be seen through and leaves were large and green. The canopies of rating 2 and rating 3 trees were defined within these rating ranges (Blazquez, 1991). Trees at the two sites were geo-referenced using the Garmin GPS12 system, compatible with soil map units by USDA-Natural Resources Conservation Service (Figs. 1 and 2). At the DeSoto site, trees were healthier than trees rated 4 at the Osceola site based on the above criteria, and tree health was not classified.

For the DeSoto site, only *Diaprepes* adult weevil data collected in 2003 were used to relate to soil data. Descriptive statistics, correlation, ANOVA and regression were done using PROC UNIVARIATE, PROC CORR and PROC GLM (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). For semivariogram analysis we used PROC VARIOGRAM (SAS Institute, 1996). Soils, trees and weevils were mapped using Arcview GIS 3.2 (Environmental Systems Research Institute Inc., Redlands, CA).

3. Results

3.1. Soil characteristics

At the Osceola site, the Mollisol (0–0.3 m) was low in pH, and Cu but high in SWC, SOM, and most of the Mehlich-I extractable ions (Table 1). A total of 50% of the Mollisol samples contained a SOM greater than the mean (80 mg kg^{-1}). Soil pH and SWC were the most skewed variables (high kurtosis values 1.2). With high Mg and K concentrations in the soil, the Ca/Mg and Ca/K ratios were small (Table 1). The Mg/K ratio was close to the ideal cation ratio recommended for plant use (Ca/Mg, 6.5/1, Ca/K 13/1, and Mg/K, 2/1) (Sopher and Baird, 1982).

At the DeSoto site, the mean soil pH was near neutral (6.6 ± 0.4, n = 100, Table 1), which was slightly higher than the optimum soil pH for citrus production (pH 6.0–6.5, Obreza and Collins, 2002). Sand content was high (Table 1), close to the average value of sand content (940 g kg^{-1}) in Florida citrus soil (Obreza and Collins, 2002). The Spodosol was high in Ca, Mg, P, and Cu but low in SOM, Fe and K (Table 1). The ratios Ca/Mg

Table 1
Comparison of mean, standard deviation (S.D.), range, and coefficient of variation (CV) of *Diaprepes* adult weevil, soil pH, soil gravimetric water content (SWC), soil organic matter content (SOM), Ca, Mg, Fe, K, P, Cu, Ca/Mg, Mg/K and Ca/K ratios, cation exchange capacity (CEC) and H%, measured in Mollisol at the Osceola site ($n = 50$), and in Spodosol at the DeSoto site ($n = 100$)

Variables	Mollisol (Osceola)[a]				Spodosol (DeSoto)[a]			
	Mean	S.D.	Range	CV	Mean	S.D.	Range	CV
Diaprepes weevils	33.1	24.8	104	75	5.1	4.1	19	80
Sand ($g\,kg^{-1}$)	527	174	708	33	900	34	176	4
Clay ($g\,kg^{-1}$)	323	143	568	44	34	15	84	44
SWC ($g\,kg^{-1}$)	260	80	339	31	135	20	96	15
pH	4.9	0.4	1.9	8	6.6	0.38	2.1	6
SOM ($g\,kg^{-1}$)	80	30	138	38	22	4	25	18
CEC ($Cmol\,kg^{-1}$)	15	4	22	26	5.7	1.6	10.4	28
Ca ($mg\,kg^{-1}$)	1263	512	3183	41	1784	602	4109	34
Mg ($mg\,kg^{-1}$)	259	93	445	36	205	59	323	29
Fe ($mg\,kg^{-1}$)	36	14	65	39	8.3	3.1	18.2	37
K ($mg\,kg^{-1}$)	114	42	212	37	27	9	44	33
P ($mg\,kg^{-1}$)	22	11	51	50	158	39	255	25
Cu ($mg\,kg^{-1}$)	0.11	0.03	0.15	31	2.8	1.1	5.9	39
Ca/Mg	4.8	1.1	8.0	23	8.9	2.4	20	27
Mg/K	2.5	1.0	4.1	40	8.2	3.6	21.5	44
Ca/K	11.9	4.7	20.7	39	73.1	41.9	320	57
H (%)[b]	42.7	9.3	43.3	22	6.4	2.9	18.3	45

[a] Data were determined in 2002 at the Osceola site, and 2003 at the DeSoto site.
[b] H (%) = 100 − base saturation.

and Mg/K, especially Ca/K (Table 1), were high, compared to the ideal cation ratios for agricultural soil (Sopher and Baird, 1982).

At each site the Mehlich-I extractable Ca concentrations had the highest standard deviation and the highest range among all soil variables (Table 1). Compared to the near neutral Spodosol at the Desoto site, the strongly acidic Mollisol at the Osceola site contained 29% less extractable Ca but 28% more extractable Mg. As plotted against soil pH, the Mehlich-I extractable Mg concentrations were more dispersed in the sandy Spodosol than in the loamy Mollisol (Fig. 3A). The regression lines showed that soil Mg tended to increase with increasing soil pH in the two soils, and there were two-best fits for the soil Mg versus pH with higher coefficient of determination for the DeSoto site ($R^2 = 0.42$**,

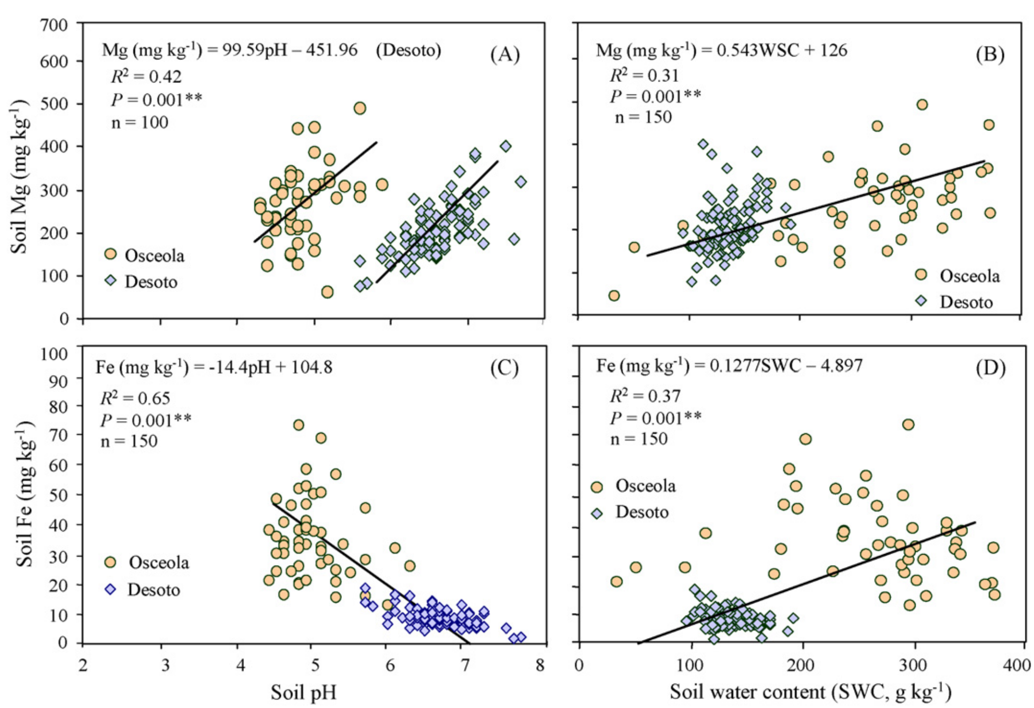

Fig. 3. Regression relationships between soil Mg concentration and soil pH (A), soil Mg and soil water content, SWC (B), soil Fe concentration and soil pH (C), and soil Fe and SWC (D) on the Mollisol at the Osceola site and on the Spodosol at the DeSoto site.

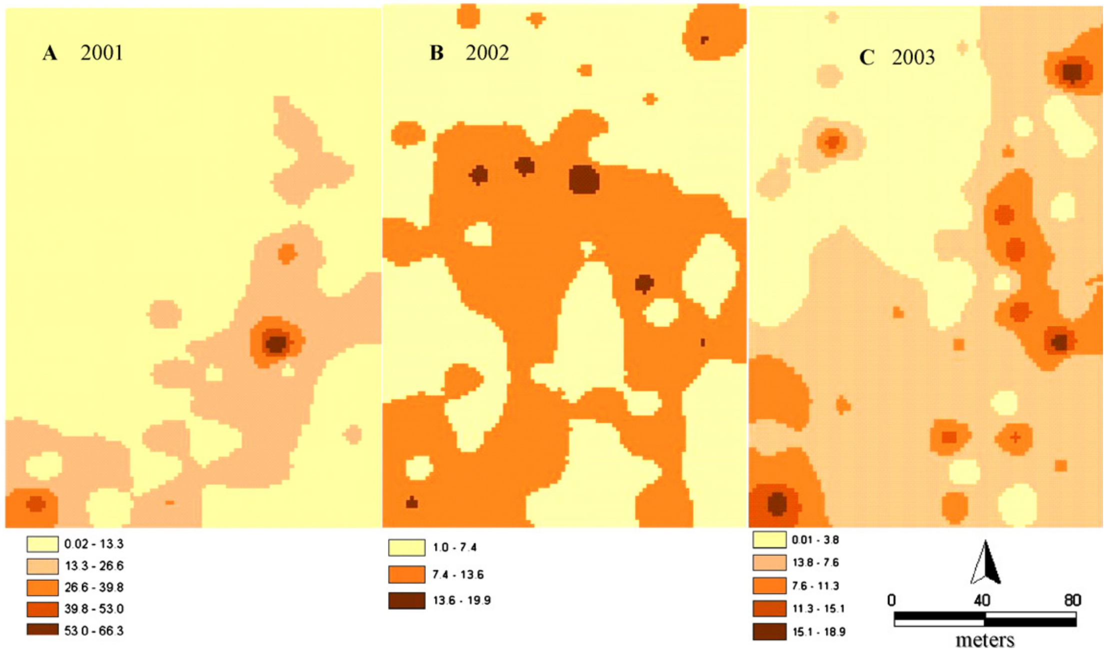

Fig. 4. Interpolated maps of *Diaprepes* root weevil distribution (adults $trap^{-1}$) in 2001 (A), 2002 (B) and 2003 (C) at the DeSoto site. Data were total number of weevils per trap ($n = 100$).

Fig. 3A). As plotted against SWC, the Mg concentrations also increased with increasing water in soils ($R^2 = 0.31^{**}$, Fig. 3B).

The Mehlich-I extractable Fe concentration in the wetter, strongly acidic Mollisol at the Osceola site was as much as four times higher than in the near neutral soil at the DeSoto site (Table 1). The Mehlich-I soil Fe concentrations decreased linearly with increasing soil pH ($R^2 = 0.65^{**}$, Fig. 3C), and increased with increasing water content in soils ($R^2 = 0.37^{**}$, Fig. 3D). The Fe was more dispersed when plotted against SWC (smaller R^2-value) than when plotted against soil pH because SWC was highly variable in the poorly drained Mollisol (Fig. 3C and D). The regression of soil Ca versus pH, and Ca versus SWC at the two sites were similar to the patterns of soil Mg versus pH and SWC (graphs not shown).

The sandy Spodosol contained 58% more sand content than the loamy Mollisol. As plotted against sand content, SWC tended to decrease linearly with sand content ($SWC = -0.2863\,Sand + 399.8$, $R^2 = 0.60$, $P < 0.001$, $n = 150$), and soil pH tended to increase with increase of sand content ($pH = 0.0035\,Sand + 3.3269$, $R^2 = 0.64$, $P < 0.001$, $n = 150$). The strongly acidic Mollisol had also 83% less extractable *P*, 96% less Cu but three times more extractable K than the near neutral Spodosol (Table 1). At the Osceola site, flooding and water saturation occurred in the central-east areas (low elevation) between December 2002 and January 2003 (Fig. 1).

3.2. Temporal variability of Diaprepes adult weevils

The *Diaprepes* weevil populations had the highest coefficient of deviation among all determined variables at the two sites (Table 1). At the DeSoto site, a total of 922, 717 and 505 adult weevils were trapped in 2001, 2002 and 2003, respectively. The weevil density showed a decreased mean and standard deviation (9.2 ± 9.9, 7.2 ± 3.8 and 5.1 ± 4.1 weevils $trap^{-1}$, $n = 100$) across the three consecutive years. The 3-year total weevil density was 21.4 ± 13.4 adults per 30 m × 15 m (per trap monitoring area). Each year, weevils were more abundant in the east and

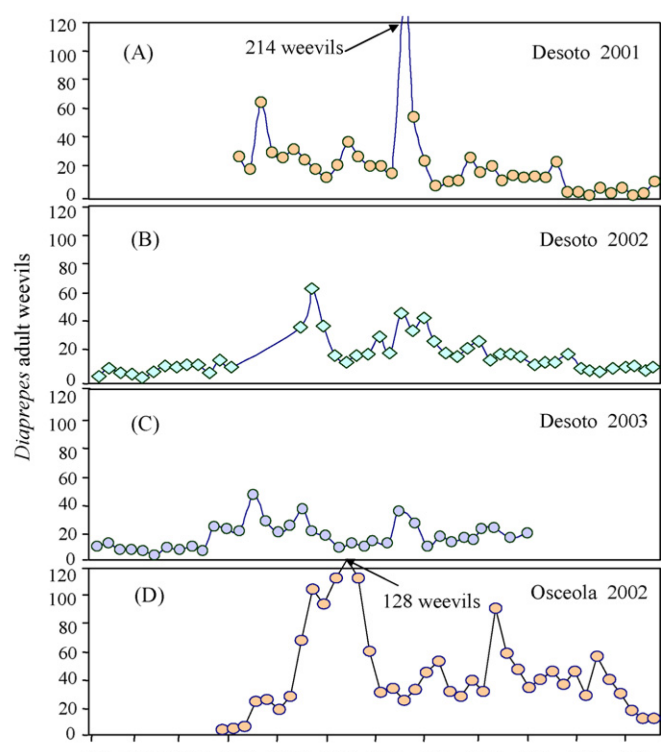

Fig. 5. Temporal patterns of *Diaprepes* adult weevils trapped in 2001 (A), 2002 (B), and 2003 (C) on the Spodosol at the Desoto site, and in 2002 on the Mollisol at the Osceola site (D).

south than other areas across the field (Fig. 4). The interpolated weevil patterns were comparable in 2001 and in 2003 (Fig. 4A and C) but the weevil distribution in 2001 was the most skewed (kurtosis 12.0, CV 107) compared to 2002 (kurtosis 0.3, CV 53) and 2003 (kurtosis 1.9, CV 80). There was a significant difference in weevil density between the 3 years (ANOVA, $F = 9.85$, d.f. = 2, 297, $P < 0.0001$). The comparison using LSD test showed a significant difference in weevil density between 2001 and 2003 ($P < 0.001$).

During 2 of the 3 years at the DeSoto site, adult weevils appeared in early January (2002, Fig. 5B; and 2003, Fig. 5C). Weevils were captured until the end of the year in 2001 (Fig. 5A) and in 2002 (Fig. 5B). Peaks of the weekly adult weevil density appeared in April, May and July across the 3 years (Fig. 5). The 3-year maximum weekly peak was 214 weevils trapped ($n = 100$) after a record weekly rainfall (146 mm) in the last week of July in 2001 (Fig. 5A). The weekly peak in 2002 (62 weevils, $n = 100$) appeared in the third week of May (Fig. 5B). In 2003, changes in weekly weevil density were not pronounced (Fig. 5C).

At the Osceola site, a total of 1655 adult weevils were captured with the 50 Tedders traps during March–December in 2002. The weevil distribution was variable with the weekly peak (128 weevils, $n = 50$) in mid-June (Fig. 5D). Comparable to the DeSoto site, the timing of the monthly peaks corresponded to the occurrence of rainfall at the Osceola site. The maximum monthly rainfall (281 mm) occurred in June 2002, while the weekly weevil population also peaked.

3.3. Spatial distribution of Diaprepes weevil, soil water, pH, Mg, and Ca

At the DeSoto site, the main effect of transect on weevil density was significant in 2001 (ANOVA, $F = 3.05$, d.f. = 5, 94, $P < 0.0136$). The weevil density was significantly higher on the T-CW in 2002 ($t = 1.99$, LSD = 2.6 weevils, $\alpha = 0.05$, error d.f. = 94) but on T-E and T-EE in 2003 ($t = 1.99$, LSD = 2.7 weevils, $\alpha = 0.05$, error d.f. = 94, Fig. 6A). Sand content was low on the T-E but the difference was not significant (Fig. 6B). Soil pH was significantly higher (mean 6.8) in the east ($t = 1.99$, LSD = 0.25, $\alpha = 0.05$, error d.f. = 94, Fig. 6C), and soil Mg concentrations were also high on the T-E (LSD = 40 mg kg^{-1}, $\alpha = 0.05$, error d.f. = 94, Fig. 6D). Distributions of soil Ca concentrations were similar to soil Mg patterns (LSD = 397, $\alpha = 0.05$). Soil gravimetric water content (0–0.3 m) showed no difference across transects (graph not shown).

At the Osceola site, per transect the weevil distribution was the most skewed on the T-W (kurtosis 28.3), and the weevil density was significantly higher on the T-C ($t = 2.014$, LSD = 18.9 weevils, $\alpha = 0.05$, error d.f. = 45) than other transects. Soil Mg increased from the west (T-W, 190 ± 73 mg kg^{-1}) to the east (T-E, 322 ± 95 mg kg^{-1}, Fig. 7A). Differences in Mg between transects were significant (ANOVA, $F = 3.70$, d.f. = 4, 45, $P < 0.0109$). Mean Ca was the highest (1450 ± 375 mg kg^{-1}) on the T-E and the lowest Ca level (908 ± 374 mg kg^{-1}) was on the T-W ($t = 2.014$, LSD = 438 mg kg^{-1}, $\alpha = 0.05$, error d.f. = 45). Soil pH was significantly lower in the west (4.6) than in the east (5.2) of the field ($t = 2.014$, LSD = 0.37, $\alpha = 0.05$, error d.f. = 45, Fig. 7B).

3.4. Tree decline versus extractable Fe and correlations of other variables

The Mehlich-I extractable soil Fe concentrations were highest (47 ± 17 mg kg^{-1}) in the center (T-C) and declined to the east and the west across the Osceola site (31–37 mg kg^{-1}, Fig. 7C).

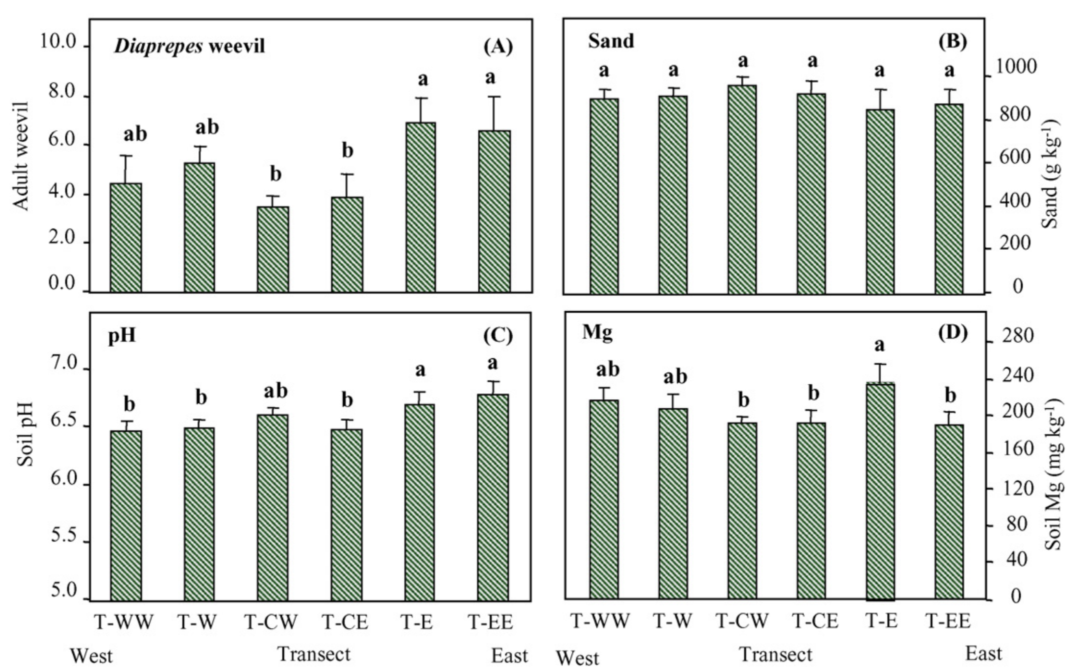

Fig. 6. Comparison of *Diaprepes* density (A), sand (B), soil pH (C) and Mg (D) at the DeSoto site. Bars (mean ± standard error) with common letters are not significant at $P < 0.05$ (LSD).

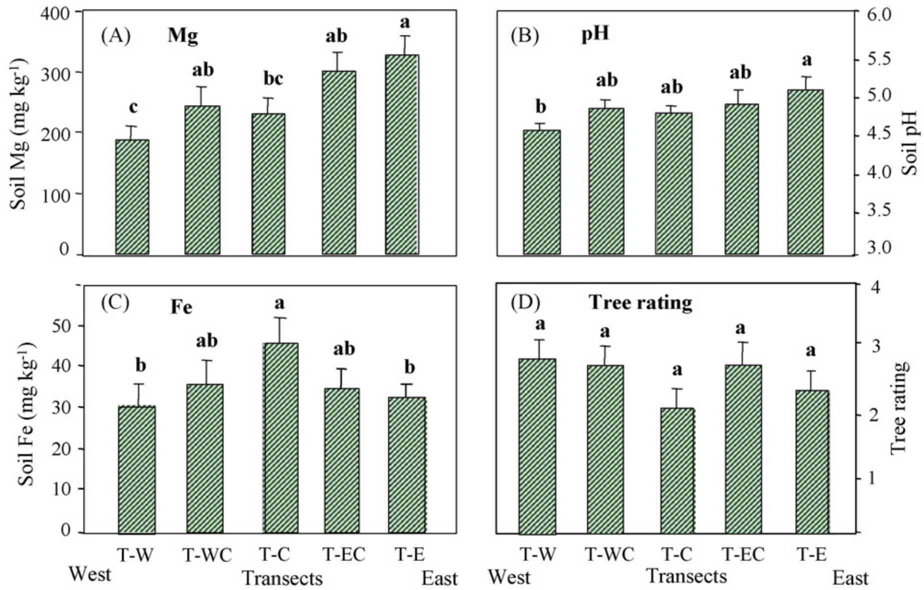

Fig. 7. Comparison of soil Mg (A), pH (B), Fe (C), and tree decline (D) at the Osceola site. Bars (mean ± standard error) with common letters are not significant at $P < 0.05$ (LSD).

The LSD comparison showed that Fe level was significantly higher on the T-C ($t = 2.014$, LSD = 12.5 mg kg^{-1}, $\alpha = 0.05$, error d.f. = 45) than the T-E and the T-W (Fig. 7C). More severe and moderately declined trees were also situated on the T-C (Fig. 7D, $P < 0.07$).

The regression plot of tree health rating (THR) against soil Fe concentration showed that tree decline was linearly correlated to soil Fe at the Osceola site (Fig. 8). More than 50% of the severely decline (rating 1) and moderately decline (rating 2) trees were situated with a high soil Fe concentration of 40–80 mg kg^{-1}. Severely decline and moderately decline trees were 60.2% of the total infested trees at the Osceola site. Only two trees of rating 3 (decline trees, or 30.9% of total infested trees) were with a soil Fe concentration >40 mg kg^{-1}. All the healthier trees (rating 4, slight decline) were in areas low in Fe concentrations between 13 and 39 mg kg^{-1} (Fig. 8). Soil Fe concentration was

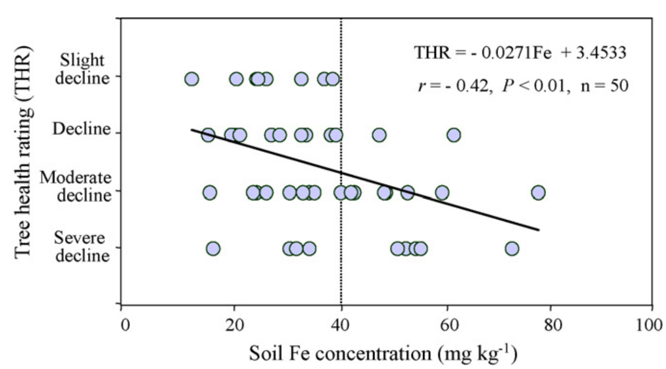

Fig. 8. Regression relationship of soil Fe concentration vs. tree decline rating (1 = severe decline, 2 = moderate decline, 3 = decline, and 4 = slight decline) on the Mollisol at the Osceola site.

Table 2
P-values of the correlation coefficients for *Diaprepes* root weevil, tree rating, and soil pH, water content (SWC), Mg and Fe on the Mollisol (Osceola site) and the Spodosol (Desoto site)

Variables	Sites									
	Mollisol (Osceola site)[a]					Spodosol (DeSoto site)[a]				
	pH	SWC[b]	Mg	Fe	Sand	pH	SWC[b]	Mg	Fe	Sand
Diaprepes	ns	ns	0.0309*	ns	ns	0.0248*	ns	0.0121**	ns	0.0282*
Tree rating	ns	ns	ns	<0.0001**	ns	–	–	–	–	–
Clay	0.0544**	0.0278*	ns	ns	<0.0001**	ns	ns	ns	ns	<0.0001**
Ca	0.0306*	<0.0001**	<0.0001**	0.0217*	ns	<0.0001**	0.0053**	<0.0001**	<0.0001**	ns
SOM[b]	0.0008**	<0.0001**	<0.0001**	0.0413*	ns	ns	<0.0001**	ns	ns	ns
K	ns	0.0088**	ns	<0.0001**	ns	ns	0.0506*	ns	ns	0.0215*
P	ns	ns	<0.0001**	0.0193*	ns	ns	ns	0.0546*	ns	ns
Cu	ns	ns	ns	0.0067**	ns	0.0015**	0.0145**	0.0002**	<0.0001**	ns
CEC[b]	ns	<0.0001**	<0.0001**	0.0448*	ns	0.0146**	0.0068**	<0.0001**	0.0435*	ns

[a] Data measured in 2002 in the Osceola field ($n = 50$), and in 2003 in the DeSoto field ($n = 100$).
[b] SWC, soil gravimetric water content; SOM, soil organic matter; CEC, cation exchange capacity. Soils in the 0–0.3 m depth.

also negatively correlated to most of the variables in the strongly acidic Mollisol (Table 2).

At the DeSoto site, the weevil population was significantly correlated among years ($0.27 < r < 0.31$, $P < 0.0059$–0.0014, $n = 100$). The weevil density in 2003 was significantly (Table 2) correlated with sand ($r = -0.22$, $P < 0.0282$), soil pH ($r = 0.23$, $P < 0.0248$), and Mg ($r = 0.25$, $P < 0.0121$, $n = 100$). Correlation coefficients of SWC, pH, SOM, Mg, Ca, and Cu varied between 0.22 and 0.70 ($P < 0.0306$–0.0001). Soil pH were significantly (Table 2) higher in areas high in extractable Mg ($r = 0.65$, $P < 0.0001$) and Ca ($r = 0.70$, $P < 0.0001$) but low in extractable Fe ($r = -0.54$, $P < 0.0001$) and Cu ($r = -0.31$, $P < 0.0015$, $n = 100$) in this Spodosol. Less soil variables (only Mg and Ca) were inversely correlated to the weevil (Mg-weevil, $r = -0.31$, $P < 0.0309$; Ca-weevil, $r = -0.26$, $P < 0.0512$, $n = 50$) in the Mollisol than in the Spodosol (Table 2).

3.5. Regression and semivariograms of weevil, soil and tree variables

The regression of *Diaprepes* adult population versus gravimetric SWC showed no significant trend for the two sites (graph not shown). However, the TDR-measured volumetric SWC was significantly correlated to the weevil population monitored in June at the Osceola site ($P < 0.05$). The regression lines showed that weevil density appeared a slight trend to decrease with increasing soil pH from 4.3 to 6.2 at the Osceola site (Fig. 9A), and a tendency of increase from 3 to 7 weevils per 30 m × 15 m ($P < 0.0248$) with increasing soil pH from 5.8 to 7.6 at the DeSoto site (Fig. 9B). Per 34 m × 25 m (monitoring areas of a trap), the weevil density decreased significantly from 54 to 12 adults with increasing soil Mg concentration from 50 to 500 mg kg^{-1} on the Mollisol at the Osceola site (Fig. 9C). The weevil density decreased from 3 to 10 adults per 30 m × 15 m ($P < 0.0121$) with increasing soil Mg from 100 to 400–500 mg kg^{-1} on the near neutral Spodosol (Fig. 9D). As plotted against sand content, the weevil density showed a very slight increase at the Osceola site (Fig. 9E) but a significant decrease ($P < 0.0282$) at the DeSoto site (Fig. 9F). Commonly, low weevil density corresponded to a soil pH range of 5.8–6.2 on the Mollisol (Fig. 9A) and Spodosol (Fig. 9B). Most of the low weevil densities also occurred with soil Mg in the range of 100–300 mg kg^{-1} on the Mollisol (Fig. 9C) and Spodosol (Fig. 9D).

Stepwise multiple linear models for the *Diaprepes* weevil population (Diap) related to SWC (g kg^{-1}) and pH, and for tree health rating (THR) related to SWC (g kg^{-1}), soil pH, and soil Fe (mg kg^{-1}) on the Mollisol at the Osceola site showed the trends as follows:

$$\text{Diap} = 139 - 0.0965\,\text{SWC} - 16.23\,\text{pH}$$
$$R^2 = 0.19, \quad P < 0.0384 \qquad (1)$$

$$\text{THR} = 4.6598 - 0.00304\,\text{SWC} - 0.03503\,\text{pH} - 0.0326\text{Fe}$$
$$R^2 = 0.26, \quad P < 0.0087 \qquad (2)$$

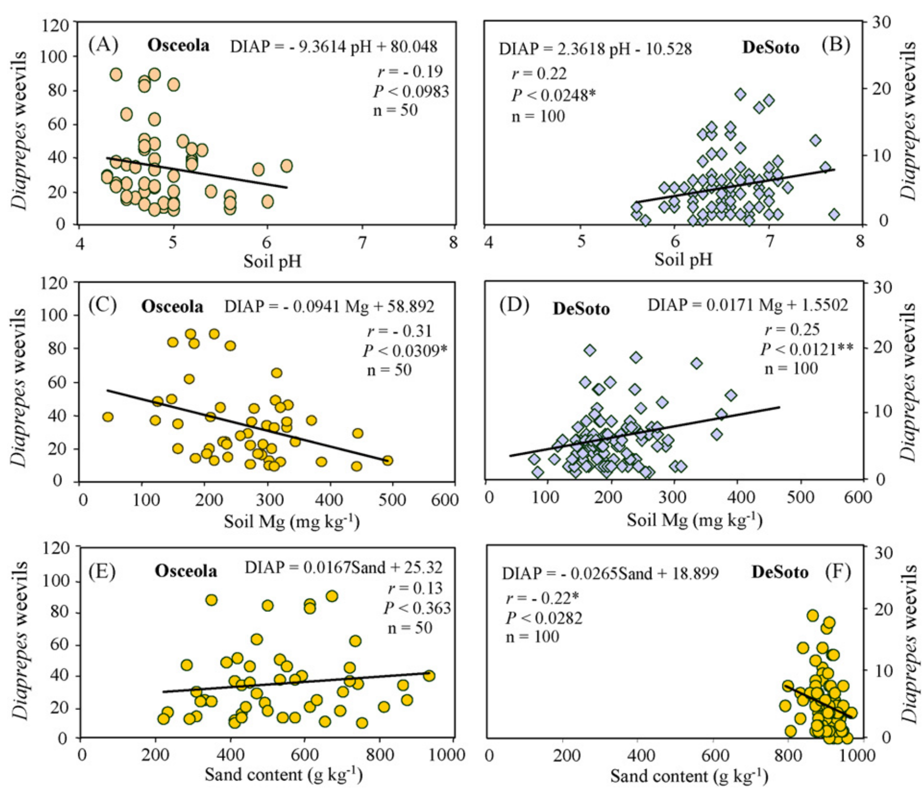

Fig. 9. Regression of *Diaprepes* adult population vs. soil pH, and *Diaprepes* adult vs. soil Mg on the Spodosol at the DeSoto site (B and D), and on the Mollisol at the Osceola site (A and C). Data were measured in 2002 at the Osceola site (E) and in 2003 at the DeSoto site (F).

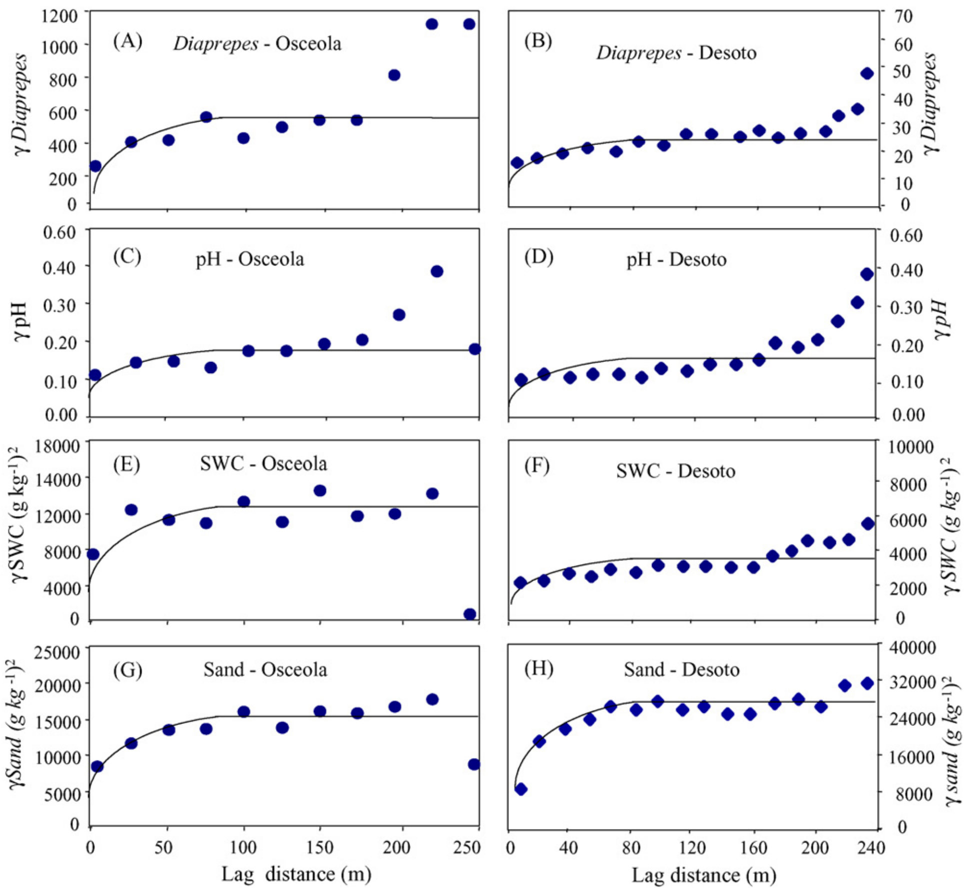

Fig. 10. Semivariograms for *Diaprepes* root weevil DIAP (A and B), soil pH (C and D), soil water content, SWC (E and F), and sand content (G and H) determined at the Osceola site and at the DeSoto site.

The model Eq. (1) was significant ($F = 3.50$, d.f. = 2, 47), and the estimate parameters were significant for the intercept ($P < 0.0021$), SWC ($P < 0.0279$), and pH ($p < 0.0361$). The model Eq. (2) was also significant ($F = 4.37$, d.f. = 3, 46), and the estimate parameters were significant for the intercept ($P < 0.0343$), and Fe ($P < 0.0017$).

The semivariogram (γ) for the *Diaprepes* weevil density was 20 times higher in the acidic and wetter Mollisol at the Osceola site (Fig. 10A) than the near neutral Spodosol at the DeSoto site (Fig. 10B), a result of 4.4 times higher weevil density on the Mollisol than on the Spodosol. The semivariogram for the weevil density tended to increase at a distance of 90 m at the DeSoto site, a larger range of 15 m than at the DeSoto site (Fig. 10B). The semivariograms for soil pH, SWC and sand were low within a range of 60–100 m with specific patterns on each site (Fig. 10C–H). Although spatial dependence of these variables occurred in a comparable range (autocorrelation distance) at the two sites, the semivariograms gave greater precision for spatial soil and weevil variability at the DeSoto site than the Osceola site. The soil and weevil monitoring distance was shorter (15 m, Fig. 2) at the DeSoto site than the Osceola site (25 m, Fig. 1), and thus more soil and weevil variability was captured at the DeSoto site.

4. Discussion

4.1. Soil water content, pH, Mg, Fe, Cu and Diaprepes weevil relations

The relationships of soil and *Diaprepes* weevil variables in the near neutral Spodosol and in the strongly acidic Mollisol at the different sites (Table 2) suggested that adult weevils captured in Tedders traps either emerged from, were attracted to, or arrested in areas with particular soil characteristics. Trees could be healthier with adequate drainage, aeration, soil pH, nutrient and water holding (related to soil texture). Larger, more densely foliated trees are likely to be good sources of food to attract weevils for feeding (Lower et al., 2003), and fuller trees may also result in more egg-laying and more neonate drop than declining trees. However, larval survival and adult density could be influenced by air temperature, soil moisture, pH and texture (Riis and Esbjerg, 1998; McCoy et al., 2003; Li et al., 2004c, 2006). Neonates dropping from trees may face many predators such as nematodes and ants in the soil (Duncan et al., 2003; Stuart et al., 2003). As a result, weevil spatial patterns could be directly or indirectly influenced by characteristics of the soils associated with the trees on which they feed (Fig. 9).

Too much Fe in soil could affect plant growth as shown by the severely declined trees in areas high in Fe concentration (Fig. 8). The high level of extractable soil Fe on the Mollisol could be due to the low soil pH (4.9, Table 1), high SWC (260 g kg^{-1}, Table 1), and flooding (Fig. 1). On many soils with a pH falling below 5.5 there could be an excessive amount of Fe, which can accumulate in the nodes and block the translocation tissues of the plant (Sopher and Baird, 1982). Soil Fe is more soluble at a low pH level, and a large amount of Fe can become available under anaerobic conditions (Bohn et al., 2001). These might explain why severely declined trees were associated with high soil Fe concentrations >40 mg kg^{-1} (Fig. 8). It could be useful to determine Fe content in plant tissues to understand the mechanism of soil Fe uptake and translocation within the soil-tree system.

The much higher extractable Cu in the Spodosol than the Mollisol (Table 1) would be a consequence of citrus tree management practices (copper fungicide applications) because up to this date the DeSoto site is still a commercial grove. This Spodosol was high in pH because the soil was formed on the Suwanne Limestone (SCS, 1989). The little effect of liming on the sol pH at the Osceola site might be because high SOM in the Mollisol (Table 1) might have complicated the reactions of dolomite with hydrogen ions (H^+). Also, floodwater and rainfall could have washed away the lime materials, dolomite. Acidic soils may contain high levels of hydrogen and aluminum that are problems for plant growth. It would be useful further determining any effects of H^+ and Al concentrations on tree health in this Mollisol.

The significantly higher weevil density on the T-C (446 weevils year^{-1}) occurring where more trees were severely or moderately declined (rating 1 and 2, Fig. 7D) suggested that tree decline could be related to the weevil in some specific areas. The significant correlations between the weevil and sand (Table 2), soil pH (Fig. 8C) and Mg (Fig. 8B and D) suggested also the impact of environmental factors on the weevil population. Sand level would affect soil aeration, drainage and water holding, thus affect both trees and weevils. In other studies, attacks of the insects on plant parts were comparable to numbers of damaging adults (Matthiessen and Learmonth, 1993), and crop yields were significantly declined due to insect infestation (Li et al., 2004a). However, leaf beetle abundance was not related to host tree leaf quality except leaf protein, and larval pupal weight was not influenced by soil water availability (Lower et al., 2003). The question of whether *Diaprepes* weevils choose high-quality host trees deserves further study.

The high SOM content in the poorly drained loamy Mollisol (four times higher SOM than in the sandy Spodosol, Table 1) could be because less oxidation of organic matter occurred under water saturation and flooding conditions (Li et al., 2004b). Soil organic matter holds water and contains nutrients, humic acids, fulvic acids and humans. Therefore SWC, and Mg and Ca concentrations were high but pH was low with high SOM in this Mollisol (Table 1). As it was the case for the Mollisol, the Mehlich-1 extractable Ca and Mg concentrations made up a large part of the CEC ($r = 0.83$ and 0.71) in the Spodosol. A possible explanation for the negative correlation of soil Mg and weevil population in the Mollisol (Fig. 8B) was that its excess Mg (mean 259 mg kg^{-1}, Table 1) could interfere with the availability of other nutrients (Bohn et al., 2001), which might have resulted in smaller trees and fewer weevils. At the DeSoto site, soil Mg concentration (mean 205 mg kg^{-1}, Table 1) would be a suitable range for growth of fuller trees that might attract adult weevils.

4.2. Management option for *Diaprepes* root weevil control

Soil pH and SWC have been among the most important variables considered in citrus production in the humid environment (Obreza and Collins, 2002). Our results suggest that soil pH management could be useful for *Diaprepes* root weevil control in certain soil environment. Mean weevil population density was the highest (40 adults trap^{-1} year^{-1}) when soil pH was low at 4.3 on the poorly drained Mollisol (Fig. 9A), and a higher soil pH within 5.8–6.2 might have led to a low weevil density (22 adults trap^{-1} year^{-1}) on this Mollisol (Fig. 9A). These regression relationships suggest the improvement of soil pH by adjusting soil liming rate for both citrus tree and weevil management (Li et al., 2004c).

The increase of extractable soil Fe concentrations with increasing SWC and the decrease of soil Fe with increasing soil pH (Fig. 3C and D) are consistent with the Fe chemistry mechanism described in Sopher and Baird (1982) and Bohn et al. (2001). Thus, increasing soil pH and improving soil drainage could also result in decreasing soil Fe level to reduce tree decline at the Osceola site. The lack of a regression relationship between SWC and the *Diaprepes* root weevil population could be because the variability of soil water was greater than other variables (Fig. 3). Soil water content varied not only with landscape positions but also with soil texture, rain pattern, and drainage capacity (Sopher and Baird, 1982; Li et al., 2001, 2002). In addition, SWC could be measured more often at the weevil monitoring times to better examine their relationships. The associations of the weevil pattern with SWC and soil aeration deserve further study.

The autocorrelation ranges determined by the semivariograms for the *Diaprepes* root weevil population, soil pH and SWC (Fig. 10) could be useful for defining tree and pest management zones for the two sites. Williams et al. (1992) found that the spatial distribution of *Limonius californicus* was spatially dependant at a range of 66 m. Spatial patterns of soil texture, pH, SOM, Mg and Ca could influence organism cycles, larval survival and plant growth (Klironomos et al., 1999; Li et al., 2002, 2004b, 2004c, 2006). These spatial data, measured in different soil types from *Diaprepes* weevil infested citrus fields, are auto-correlated with a distance ranging between 60 and 100 m (Fig. 9). These spatial correlation ranges could be used with GIS tools to delineate management zones for root weevil control at the field scale (Li et al., 2004b). Controlling the root weevil by zone should be more practical and less costly.

The multiple linear models (Eqs. (1) and (2)) have increased significantly the model predictive power (R^2) compared to the simple linear models (Fig. 9). More spatial variables were included and thus more data variances were explained in the multiple linear models. In the poorly drained Mollisol, future *Diaprepes* adult population should decrease significantly with SWC and pH (Eq. (1)), and that the trees should improve from high tree rating (severe or moderate decline) to low tree rating (decline or slight decline) with decreasing soil Fe by the importance of its estimate parameter (Eq. (2)), Fe concentration, and the probability ($P<0.0017$ for Fe parameter). However, from practical point of view, simple linear models are more comprehensive in showing the relationship between two variables (Fig. 9). These simple linear models are easier to understand, more practical, and less costly to put into practice in predicting and controlling the outcome in the future.

Although both study sites were on poorly drained flatwoods, the differences in landscape position (linked to drainage, etc), soil characteristics and management history between the sites suggested that tree and *Diaprepes* management should be established on a site-specific basis. For example, the high soil Ca and Mg at the Osceola site could be associated with liming, and it would be originally associated with the geology (limestone as surface sediments) at the DeSoto site. Also, because few data were measured in the flooded areas (Fig. 1), it was not clear whether waterlogging has influenced soil pH, and Fe, Mg and Ca concentrations and their distribution patterns within these sites. In addition, since lime was uniformly applied, what factors could cause higher soil pH level in the east than other areas at the Osceola site (Fig. 7B)? There is still a need for more information about the relationships between weevil population, landscape position, soil type, SWC, pH, and nutrient concentrations from more sites across the state.

5. Conclusions

The relationships between soil heterogeneity, citrus trees, and *Diaprepes* root weevil spatial patterns, determined from the two-site data, have yielded insights for site-specific management of citrus trees and the root weevil. Soil pH could be critical to sustaining agricultural productivity in certain Florida citrus soils because of its association with soil Fe, Mg and Ca concentrations and with *Diaprepes* root weevil patterns. The large dispersion of soil Mg and Fe concentrations versus SWC and soil pH at the two sites indicated highly variable of soil properties that could influence tree and weevil patterns. Site variations can complicate management practices for improving soil and tree conditions while minimizing the impact of *Diaprepes* root weevils. No single measurement could describe the influence of soil characteristics on tree decline and root weevil variability. It was suggested that a soil pH of 5.8–6.2 could lead to a low weevil density of 22 adults $year^{-1}$ per $34\,m \times 25\,m$ on the Mollisols. Separating plant stresses from soil acidity, water logging and root weevil feeding will require data from a broader range of sites. With site-specific management based on soil characteristics and landscape position, the soil-weevil-tree simple linear models would be appreciate to put into practice in predicting and controlling the weevil population and tree decline in the future.

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