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Nutrient management zones for citrus based on variation in soil properties and tree performance

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Abstract Site-specific soil management can improve profitability and environmental protection of citrus groves having large spatial variation in soil and tree characteristics. The objectives of this study were to identify soil factors causing tree performance decline in a variable citrus grove, and to develop soil-specific management zones based on easily measured soil/tree parameters for variable rate applications of appropriate soil amendments. Selected soil properties at six profile depths (0–1.5 m), water table depth, ground conductivity, leaf chlorophyll index, leaf nutrients and normalized difference vegetation index were compared at 50 control points in a highly variable 45-ha citrus grove. Regression analysis indicated that 90% of spatial variation in tree growth, assessed by NDVI, was explained by average soil profile properties of organic matter, color, near-infrared reflectance, soil solution electrical conductivity, ground conductivity and water table depth. Regression results also showed that soil samples at the surface only (0–150 mm) explained 78% of NDVI variability with NIR and DTPA-extractable Fe. Excessive available copper in low soil organic matter areas of the grove apparently induced Fe deficiency, causing chlorotic foliage disorders and stunted tree growth. The semivariograms of selected variables showed a strong spatial dependence with large ranges (varied from 230 m to 255 m). This grove can be divided into different management zones on the basis of easily measured NDVI and/or soil organic matter for variable rate application of dolomite and chelated iron to improve tree performance.

Keywords Leaf nutrients · Management zones · NDVI · Soil organic matter

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Introduction

In spite of the large-scale spatial variability of soil fertility, water table depths, and tree performance in Florida citrus groves, the typical management practices consist of applying uniform rates of inputs across large groves. The spatial variation of soil properties may lead to variable tree performance and decreased resource use efficiency (Schumann et al. 2003). To accommodate such variation, one may design a precision agriculture system as opposed to the conventional practice of applying one uniform rate over large areas (Ndiaye and Yost 1989; Whitney et al. 1999). Development and ultimate use of variable rate management practices requires accurate identification and assembling of appropriate data, reliable interpretation, analysis and proper economic management of within-field variation (Mulla and Bhatti 1997).

One of the major deficiencies in most of the sandy citrus soils of Florida is an acute shortage of organic matter (Tarjan 1977). Organic matter often determines soil water retention, storage and release of plant nutrients, adsorption of pesticides and nitrogen (N) availability to plants. Organic matter can vary according to the spatial variation of the factors that affect its accumulation and decay: temperature, pH, moisture content, oxygen availability, soil texture, microbial populations and management (Jenkinson 1988). Florida citrus soils are commonly low in both macronutrients and micronutrients, which can limit tree function (Jackson et al. 1995). Iron deficiency occurs in plants growing in alkaline soil, waterlogged soils, or in soil very low in organic matter (Jackson et al. 1995). Other Fe deficiency problems have occurred where high levels of Cu are present (Alva and Chen 1995) as excess Cu can cause Fe chlorosis even in acid soils (Smith et al. 1950; Reuther and Smith 1952).

Typically, a fertilizer recommendation is based on the average of a few soil or leaf test samples under one uniform rate of fertilizer over the entire grove. This average recommendation will result in high yielding or large trees in the grove receiving relatively less fertilizer than they require and low yielding or small size tree areas receiving relatively more fertilizer than necessary (Schumann et al. 2003; Zaman et al. 2005). Local over-fertilization may decrease ground water quality, reduce profit margins, induce deficiency of other elements and interfere with metabolic processes. Under-fertilization may restrict citrus yield and quality. Variable rate application avoids these problems but requires knowledge of the scale of variability of soil and tree characteristics within each field and whether such variability is random or patterned and the precise nutritional requirements (Mulla and Bhatti 1997).

The most convenient way to represent surface area variation is by means of maps. The reliability of mapping depends upon the sampling scheme. An efficient sampling scheme is one in which the minimum number of sample locations are obtained for mapping to characterize the magnitude of soil variability (Kerry and Oliver 2003). Cost is usually directly proportional to sample number and can be compared with efficiency of attribution in a procedure, similar to fertilizer cost: benefit ratio (Hall 1921).

Fertilizer recommendations based upon soil sampling are time consuming and expensive. Thus alternate approaches are needed that estimate spatial patterns in fertilizer requirements with reasonable accuracy, yet do not require extensive soil sampling. The normalized difference vegetation index (NDVI) calculated from easily available aerial photography of citrus groves (http://data.labins.org/2003/MappingData/DOQQ/doqq_99_utm.cfm) could be used for making sampling strategy and management zones. NDVI can be used for relative estimation of citrus tree health, vegetation vigor and density

(Fletcher et al. 2004). Whitney et al. (1999) described yield maps showing spatially variable yield significantly correlated to tree canopy size determined from aerial photography. Zaman et al. (2004) found highly significant correlation between NDVI and ultrasonically-sensed and manually measured tree volumes.

Management zones can be useful for variable rate application of crop inputs using the spatial analysis tools of precision agriculture for improved crop management (Ferguson et al. 2003). There are numerous proposed methods for delineating management zones (Bhatti et al. 1991; Shanahan and Schepers 2003), often varying with the management inputs under consideration, but generally relying on spatial information that is stable or predictable over time and related to crop productivity (Doerge 1999). Recent technology involving GPS guided prescription map-based fertilizer spreading or real time sensing has been developed to manage groves site-specifically (Miller et al. 2003). Chan et al. (2002) examined the effects of interpolation method, boundary determinations and GPS location errors on variable rate fertilizer application maps derived from yield maps. They explained that boundary offset had the greatest influence on mean absolute error followed by the GPS horizontal error and the interpolation method. Miller et al. (2003) tested a variable rate granular fertilizer spreader with both prescription mapping and real-time sensing with photocells in citrus groves. The variable rate fertilizer unit performed well for site-specific fertilizer application. As a result, some technological barriers to managing groves with variable rate of inputs have largely been overcome. Therefore, there is a great need to divide groves into appropriate management zones, using more intensive and cheaper ancillary data, that receive different rates of soil nutrients to increase input efficiency and decrease ground water pollution.

The objectives of this study were:

1. To identify the most significant soil variables that affect citrus tree growth in a selected grove.
2. To quantify the spatial patterns of variability in NDVI, soil parameters and leaf nutrients, and
3. To divide a citrus grove into management zones for variable rate soil amendment application on the basis of easily measured soil and tree characteristics.

Materials and methods

Grove history

Revell citrus grove was selected near Bowling Green in Hardee county, Florida, USA (27.63089° N, 81.82467° W). The grove has no artificial drainage and is planted with a mixture of mature '*Hamlin*' and '*Valencia*' orange trees on *sour orange* rootstock at 9.2 × 4.6 m spacing. The grove is 789 m E–W and 712 m N–S at an elevation of 33.5–38.1 m, above mean sea level (Fig. 1). An aerial photograph taken by Land Boundary Information System, Florida Department of Environmental Protection in 1999 (Labins, 1999) shows large spatial variability in tree canopy cover within the grove (Fig. 1). Ground inspections revealed that low canopy cover was due to both stunted mature trees and gaps where mature trees had died and young ''resets'' had been planted.

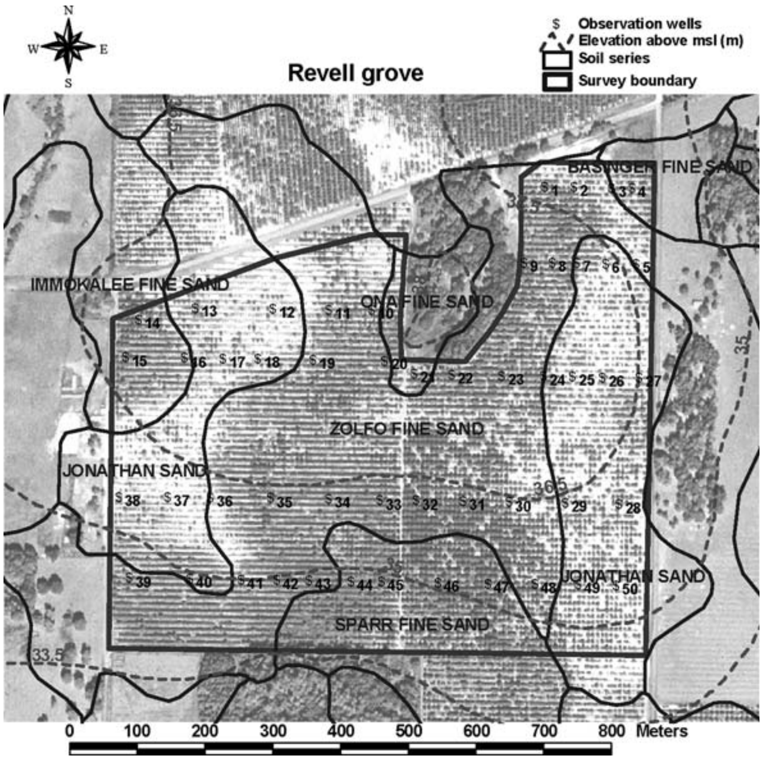

Fig. 1 Aerial photograph of the Revell grove, showing location of 50 observation wells, elevation contours, soil series, and the survey boundary for this study

The poorer areas of the grove are mainly on Jonathan sand whereas the more productive areas of the grove are predominantly on Zolfo fine sand (Fig. 1). These soils are Spodosols and are characterized by shallow seasonal perched water tables formed when surface water infiltrates rapidly through the loose sandy A and E horizons and accumulates over the very slowly permeable structured and sometimes cemented spodic (Bh) subsoil horizon.

Water table depth measurements

Fifty water table observation wells were installed during the dry season (March 2002) in the grove as an irregular grid. Wells were positioned from a 1999 digital aerial photograph of the grove using a Garmin XL12 Global Positioning System (GPS; Garmin International Inc., Olathe, KS, USA) and Fugawi moving map software (Northport Systems Inc., Toronto, Canada) on a laptop computer to cover the major observable citrus tree variability (Fig. 1). Each well consisted of a 1.5-m long, 100-mm diameter PVC pipe, perforated with 25-mm holes in the lower 1.1-m section and covered with nylon drain sleeve to prevent soil entry. A PVC end-cap was placed over the top end of the pipe to prevent water or soil from entering. Wells were located in the citrus tree rows, between two tree trunks. Measurements of water table depth in the wells were made using a flexible steel measuring tape during July, 2002.

Soil properties, leaf nutrients and tree canopy size measurements

Soil profile samples were taken from six depths (0–150, 150–300, 300–600, 600–900, 900–1200, 1200–1500 mm) at each well site and analyzed for soil pH, soil organic matter (SOM), soil solution electrical conductivity (EC_{lab}), exchangeable acidity (EA), soil texture (sand, silt, and clay), DTPA-extractable iron (Fe), soil colors (L*, a*and b* representing lightness, red-green and yellow-blue scales, respectively) (CIE-Commission International on de l'Eclairage Light 1976) during March, 2002.

Measured SOM was compared with near-infrared (NIR) spectrometer readings for all soil samples. The EC_{lab} of soil samples was determined with air-dry subsamples in the laboratory using a 2:1 (water:soil) extraction and an Accumet 50 (Fisher Scientific, Hampton, NH, USA) electrical conductivity meter. Soil pH was measured in a 1:2.5 soil: water ratio using a Corning 450 (Corning, Incorporated, NY, USA) pH meter. Near-infrared absorbance readings at 1194 nm and soil colors were obtained using a near-infrared Cannon CF60 – T31AN1D (Canon Precision Inc., Japan) spectroscopy and EPP2000- VIS- 100 (StellarNet, Inc., FL, USA) digital colorimetry, respectively. Soil texture was calculated using the pipette method (Moody et al. 1959). Exchangeable acidity, SOM and Fe of soil samples were determined according to the standard methods described in Sparks (1996).

Ground conductivity measurements were taken at each well site when the water table was measured. An EM38 model electromagnetic profiler (Geonics Limited, Mississauga, Ontario, Canada) was used to measure profile conductivity at ground level in both the horizontal dipole (EM_h) and vertical dipole (EM_v) orientations.

Five leaves from each of six trees at each well site were selected to take the chlorophyll index readings using a SPAD-502 Chlorophyll Meter (Minolta Corporation, New Jersey, USA). Four months old (mature) spring-flush leaf samples from non-bearing branches were collected during July around each well site according to procedures described by Obreza et al. (1992). Leaves were washed, dried at 70°C for 48 h and ground to pass a 0.38-mm sieve. Leaf nitrogen (N) was determined by the Kjeldahl method and phosphorus (P), potassium (K), calcium (Ca), magnesium (mg), manganese (Mn), sulpher (S), copper (Cu), zinc (Zn), iron (Fe), and boron (B) concentration were determined by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP – AES).

The NDVI was calculated from aerial photography of the grove with Ag 20/20 (Institute for Technical Development, National Astronautics and Space Administration, FL, USA) extension for ArcView GIS software using the following formula (Jensen 1996).

$$NDVI = \frac{(\rho_{\mathrm{nir}} - \rho_{\mathrm{red}})}{(\rho_{\mathrm{nir}} + \rho_{\mathrm{red}})} \tag{1}$$

Where ρ is the reflectance and ''nir'' is near-infrared radiation and ''red'' is red radiation.

The non-tree signals were included in the NDVI calculations.

The resulting NDVI indices were converted into percentage, the most dense (healthier) trees with the highest NDVI were rated as 100% and the relative percentage was calculated for remaining, lower NDVI indices.

Manual tree volume computation

A digital pole (Senshin Industry Co., Ltd. Japan) and measuring tape were used to measure the height and diameters of selected trees at 50 sampling points to compute the manual volume (MV). The formula used for MV was based on one-half of an ellipsoid considering canopy diameters parallel and perpendicular to the row (near ground level) and maximum canopy height (Tumbo et al. 2002). The manual tree volumes were compared with NDVI values for selected trees in the grove.

Lime (Dolomite) and iron requirement for different management zones

The lime (dolomite) (kg ha^{-1}) requirement for low, medium and high management zones based on the variation in NDVI and SOM was calculated (based on pH goal and amount of exchangeable acidity measured) for low, medium and high management zones. The elemental Fe (kg ha^{-1}) requirement was also calculated for different management zones according to the recommendations reported by Ferguson et al. (1995).

Data analysis

The soil profile depth-weighted average of measured soil properties, NDVI and leaf nutrient data were analyzed using classical statistical techniques to obtain the mean, standard deviation, skewness, and coefficient of variation (Steel and Tori 1980). The NDVI and corresponding soil properties were analyzed with Genstat statistical software (Genstat 5, Lawes Agricultural Trust, Rothamsted, UK) by stepwise multiple linear regression to identify significant effects of soil properties on tree performance. The correlation procedure was used to find the relationship between NDVI, water table depth, soil properties, tree volumes and leaf nutrients. The mixed procedure (SAS Institute, Cary, NC, USA) was used to compare the means and matching means of selected variables and NDVI were separated by the *t*-test at 5% level of significance.

Geostatistical analysis was performed using the GEO-EAS (Englund and Sparks 1991) geostatistical software package to calculate and model variograms for NDVI, chlorophyll index, soil properties and leaf nutrients. The standard semi-variogram models were fitted (based on a criterion of goodness of fit) to the semi-variance data for quantifying the scale and intensity of spatial variation in NDVI, soil properties and leaf nutrients (Mulla et al. 1992; Webster and Oliver 2001).

The DGPS coordinate data file was joined to the soil and tree parameters data files and imported into ArcView GIS software (Environmental Systems Research Institute [ESRI], Redlands, CA, USA), for mapping. Regular gridded XYZ data surfaces were interpolated at unsampled locations using kriging techniques to provide additional data for detailed mapping using point kriging and eight search sectors with the Surfer 7 software (Golden Software Inc., Golden, CO, USA). The different management zones (low, medium and high) were identified on the basis of variation in NDVI in the grove using NDVI pixel classification in ArcView GIS. The DGPS guided prescriptions maps were produced using GIS for the variable rate application of appropriate soil amendments using a variable rate fertilizer spreader.

Results and discussion

Statistical analysis

The summary statistics indicated large variation (high CVs) for NDVI and selected soil variables except for soil color (L*) and soil pH (Table 1). According to a relative ranking

Table 1 Summary statistics for NDVI, soil properties and leaf nutrients

Soil/Leaf Property	Min–Max	Mean	CV (%)	Skewness
NDVI (%)	2.52–86.44	45.63	51.78	−0.34
SOM (g kg^{-1})	1.20–16.90	6.30	67.04	0.83
Fe (mg kg^{-1})	0.38–4.49	1.79	57.60	0.68
NIR absorbance	0.14–0.32	0.22	21.59	0.089
a*	1.46–4.37	2.68	33.04	0.12
b*	3.81–14.16	8.69	38.03	−0.091
L*	51.89–82.61	68.18	12.77	−0.031
EC_{lab} (mS m^{-1})	2.25–14.13	6.55	39.91	0.71
EM_v (mS m^{-1})	4.10–12.50	7.56	29.88	0.39
Wd (mm)	0–1246.00	559.3	60.50	0.28
Soil pH	5.15–6.88	6.10	6.61	−0.08
EA ($cmol^+$ kg^{-1})	0.09–0.55	0.25	43.00	0.78
Leaf Nutrient	Min–Max	Mean	CV (%)	Skewness
Chlorophyll index	48.25–82.40	67.33	14.50	−0.23
N (g kg^{-1})	24.90–34.90	29.40	7.86	0.16
P (g kg^{-1})	1.20–1.80	1.50	11.02	−0.21
K (g kg^{-1})	9.10–28.60	13.70	29.00	1.54
Ca (g kg^{-1})	28.40–50.30	38.40	13.50	0.18
Mg (g kg^{-1})	2.10–5.20	3.70	22.23	−0.05
S (g kg^{-1})	2.50–4.80	3.20	12.74	1.36
Cu (mg kg^{-1})	9.24 −35.16	15.40	30.48	1.72
Fe (mg kg^{-1})	54.81–121.96	72.62	15.09	2.12
Mn (mg kg^{-1})	7.33–41.48	18.76	45.93	0.99
Zn (mg kg^{-1})	14.09–38.06	21.47	23.14	0.94
B (mg kg^{-1})	22.76–254.62	57.03	78.63	3.53

scheme for variability of soil properties proposed by Wilding (1985), the variability of NDVI and observed soil properties in this study ranged from moderate to high except soil color L* and soil pH. The leaf nutrients exhibited low to moderate variation except B and Mn where %CV was relatively high. According to the nutrient recommendations for citrus trees (Hanlon et al. 1995), leaf Cu was higher and soil Fe, leaf Zn and leaf Mn were lower than the optimum level in the Revell grove. The other observed nutrients were generally at optimum level (Hanlon et al. 1995). Variability in various soil properties, water table depth, leaf nutrients and NDVI was non-random (Table 1).

Stepwise multiple linear regression analysis indicated that 90% of spatial variation in tree growth, assessed as NDVI, was explained by average SOM, soil colors (a* and b*), NIR, EC_{lab}, EM_v and Wd.

Regression results also showed that more easily collected soil samples taken at the surface only (0–150 mm) explained 78% of NDVI variability with NIR and soil Fe.

The correlation between NDVI and manual tree volumes (MVs) were highly significant ($r = 0.81$). Some discrepancies between MVs and NDVI values in the grove originated from the four year-old aerial photographs which did not reflect recent grove changes. When the very young trees (3 replants) were removed from the data set, the correlation coefficient was increased by 7.4% ($r = 0.87$). The very small size trees in the grove were from resetting after tree loss from freezes and disease. The strong significant correlation between MVs and NDVI supports the idea that NDVI could be used to estimate tree size and vegetation vigor (Fletcher et al. 2004).

Simple correlation coefficients (r) between NDVI and either measured SOM or soil Fe had values 0.69 and 0.57, respectively (Table 2). These relationships show that as the SOM

Table 2 Correlation matrix of NDVI and selected soil properties

Soil Property	NDVI	EM_h	EM_v	OM	EC_{lab}	EA	pH	Fe	L*	a*	b*	NIR
EM_h	0.479											
EM_v	0.471	0.855										
OM	0.694	0.329	0.396									
EC	0.210	0.514	0.528	0.322								
EA	0.442	0.132	0.100	0.639	0.265							
pH	−0.212	−0.198	−0.408	−0.359	−0.409	−0.409						
Fe	0.573	0.208	0.257	0.736	0.485	0.559	−0.399					
L*	−0.826	−0.458	−0.466	−0.864	−0.311	−0.577	0.268	−0.768				
a*	0.873	0.493	0.477	0.784	0.307	0.512	−0.342	0.715	−0.914			
b*	0.738	0.079	0.030	0.633	0.116	0.396	−0.190	0.614	−0.635	0.728		
NIR	0.786	0.356	0.420	0.931	0.334	0.581	−0.375	0.788	−0.933	0.843	0.662	
Wd	−0.249	−0.738	−0.897	−0.261	−0.426	0.071	0.416	−0.207	0.356	−0.350	0.110	−0.326

5% level of significance $|r| \geq 0.273$

1% level of significance $|r| \geq 0.354$

0.1% level of significance $|r| \geq 0.443$

and soil Fe increased, the tree growth increased and vice versa. Correlation coefficients relating SOM to soil Fe or NIR had values of 0.74, 0.93, respectively. There was also positive correlation between SOM and soil colors (a* and b*). The strong significant correlation between SOM and either NIR, or soil colors (a*, b* and L*) supports the idea that these easily and rapidly measured soil properties could be used to estimate and map SOM on- the- go within a grove (Sudduth and Hummel 1993; Laird and Christy 2003).

There was significant negative correlation between leaf Cu and either NDVI or soil Fe ($r = -0.46$ and -0.44, respectively) and significant positive correlation between NDVI and soil Fe ($r = 0.57$) indicating that excess Cu probably induced iron deficiency in citrus trees. Iron deficiency was visible as chlorotic foliage, stunted and thickened trees with lack of branches. These observations are in accordance with previously reported studies (Alva and Chen 1995; Reuther and Smith 1952). Leaf chemical analysis for Fe was found to be a poor indicator of response in this study and in the literature (Burns et al. 1974). Leaf chlorophyll index, an indicator of leaf Fe status, had significant negative correlation with leaf Cu ($r = -0.41$) and significant positive correlation with soil Fe ($r = 0.73$) which also suggests the potential role of Cu in inducing Fe deficiency. Zinc and Mn were deficient within the grove (Table 1), but Mn did not affect tree growth significantly (Table 3). Alva and Chen (Alva and Chen 1995) also reported that increased Cu concentration reduced Zn, Fe and Mn uptake by seedlings, but the effect of Cu was more pronounced on the uptake of Fe than on that of Zn or Mn. The leaf Mg had a positive correlation with NDVI ($r = 0.54$) and SOM ($r = 0.70$).

Geostatistical analysis

The semivariograms for NDVI, soil properties (SOM, soil Fe, NIR and pH) and leaf variables (chlorophyll index, Cu, Mg) were computed and a spherical model was found to best fit the data sets. The model parameters (sill, nugget and range) of semivariograms for NDVI, soil properties and leaf variables revealed non-random spatial patterns within the grove (Table 4). The semivariograms of NDVI and SOM are presented in Figs. 2a, b as an example. Approximately 11, 14 and 26% variation in measured NDVI, SOM and soil Fe, respectively, at this study site were unexplained. This unexplained variation might be due to variability at large scales of sampling interval used for this study or to variability

Table 3 Correlation matrix of NDVI and leaf nutrients

Leaf Nutrient	NDVI	Chlorophyll	N	P	K	Ca	Mg	S	Mn	Fe	Zn	Cu
Chlorophyll	0.908											
N	−0.083	0.040										
P	−0.296	−0.216	0.728									
K	−0.186	−0.078	0.695	0.612								
Ca	0.148	0.102	−0.539	−0.337	−0.706							
Mg	0.539	0.464	−0.254	−0.192	−0.390	0.105						
S	−0.444	−0.509	0.444	0.535	0.139	0.076	−0.255					
Mn	−0.214	−0.167	−0.056	−0.220	0.173	−0.116	−0.396	−0.150				
Fe	0.258	0.145	0.027	0.021	−0.070	0.082	0.225	0.045	−0.223			
Zn	−0.319	−0.288	0.187	0.072	0.347	−0.042	−0.425	0.233	0.704	−0.290		
Cu	−0.475	−0.412	0.024	0.186	−0.209	0.375	0.072	0.415	0.070	−0.141	0.223	
B	0.066	0.126	0.046	-0.082	0.192	−0.267	0.416	−0.320	0.172	−0.057	−0.116	−0.299

5% level of significance $|r| \geq 0.273$

1% level of significance $|r| \geq 0.354$

0.1% level of significance $|r| \geq 0.443$

resulting from measurement errors (Mulla et al. 1992; Oliver 1987). These results suggest that although sampling distance for soil and tree characteristics were effective for evaluating spatial variation, more (closer spaced) data points might be needed to understand the uncertainty (variance) of variables. The nugget for Wd equals zero when lag distance is zero. This is expected, since there should theoretically be no variation in sample values that are measured at the same location (Bhatti et al. 1991).

The scale of spatial correlation varied in distance from 230 m to 255 m for NDVI, selected soil properties and leaf nutrients (Table 4). At distances shorter than this range, variability is non-random (Oliver 1987). The results show that selected soil and tree characteristics vary at large spatial scales, and there are correlations between several soil and tree characteristics (Tables 2 and 3). Kerry and Oliver (2003) suggested that the sample spacing be from one third or less than half the range of variograms. The results of this study suggest that a sampling interval ~100 m, would provide reliable predictions for managing the within grove variation. This emphasizes the need to adjust sampling intensity to the range of spatial dependence to avoid unnecessary sampling and analytical cost.

Interpolation and mapping

The interpolation technique, kriging, was applied to the data sets (NDVI, SOM, soil Fe, NIR, pH, leaf chlorophyll index, leaf Cu, and leaf Mg) to produce detailed maps. Since the means of kriged data sets were closer to the mean of measured properties (Table 5), the kriging estimates appear to be very accurate and are better than simpler methods such as inverse distance weighting or trend surface models (Mulla et al. 1992). The variability (CVs) of kriged data sets were also in the same relative ranking as the variability in measured data sets in this study (Wilding 1985) (Tables 2 and 5).

The map of NDVI based on an image of 1 m resolution for the whole grove was better than the kriged NDVI map based on NDVI calculated for selected trees at 50 sampling points with minimum distance of ~50 m between two sampling points (Figs. 3a and b). Some of the within-soil type variation in tree conditions is lost when using kriging technique due to the coarser manual measurements (Figs. 1 and 3a) of soil and tree parameters. The percentage of areas having low, medium and high NDVI values in three (low, medium and high) management zones are approximately the same for kriged estimates of NDVI and NDVI calculated using the entire grove image (Table 6).

Table 4 Summary of parameters for spherical semivariogram models (soil properties and leaf nutrients significantly affecting tree growth)

Soil Property/ Leaf Nutrients	Sill	Nugget	Range (m)
NDVI	520	56.0	238
SOM	16.0	2.20	235
Soil Fe	1.04	0.27	238
NIR	0.0022	0.00018	230
a*	0.767	0.061	243
b*	10.70	2.00	245
EC_{lab}	6.69	1.70	250
EM_v	5.00	0.38	250
Wd	11,700	0.00	250
Soil pH	0.17	0.026	230
Chlorophyll index	93.96	4.50	255
Leaf Mg	0.064	0.010	255
Leaf Cu	22.37	9.25	234

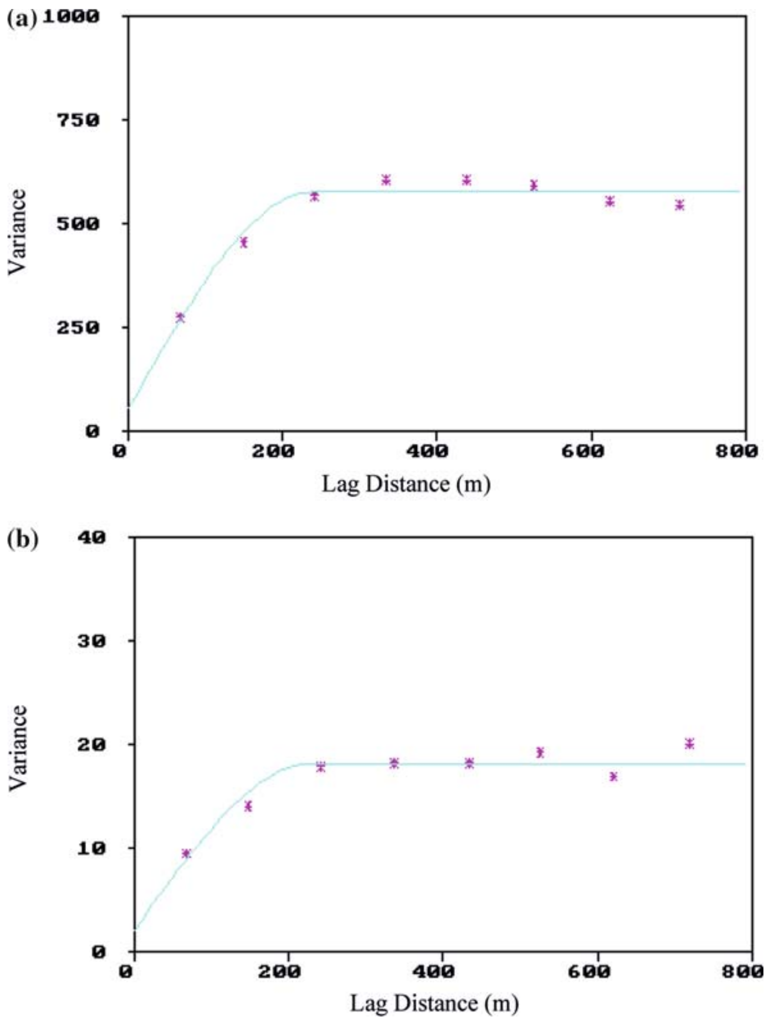

Fig. 2 Semivariograms for (**a**) NDVI and (**b**) SOM

Table 5 Statistical summary for kriged data of NDVI, selected soil properties and leaf nutrients

Soil Property/Leaf Nutrients	Min–Max	Mean	CV (%)
NDVI (%)	3.18–86.28	45.68	40.78
SOM (g kg^{-1})	1.20–16.50	6.20	47.50
Soil Fe (mg kg^{-1})	0.38–4.42	1.83	45.27
EA (cmol^{+} kg^{-1})	0.10–0.54	0.25	30.02
Soil pH	5.17–6.88	6.14	5.20
NIR absorbance	0.14–0.32	0.22	17.60
Chlorophyll index	48.53–82.27	67.37	14.54
Leaf Cu (mg kg^{-1})	9.49–34.86	15.61	22.04
Leaf Mg (g kg^{-1})	2.10–5.20	3.70	17.35

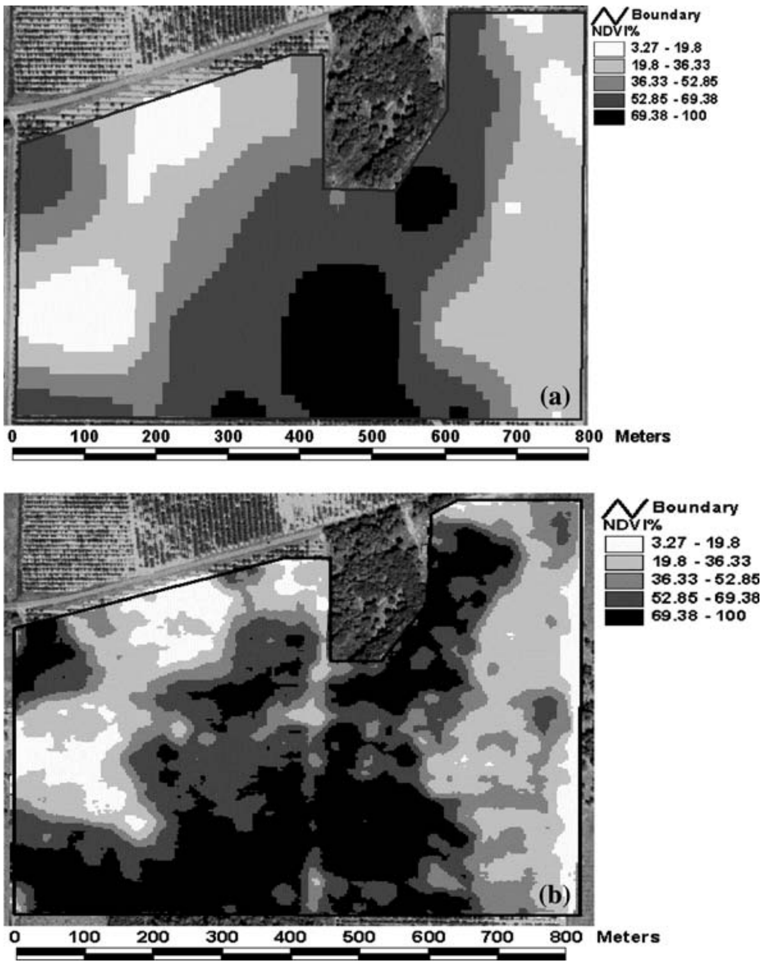

Fig. 3 Map of NDVI (**a**) Kriged estimates of NDVI using 50 trees (**b**) using aerial photograph and Ag 20/20 software

Table 6 The percentage of total grove area lying in the regions having low, moderate and high values of NDVI, soil variables and leaf nutrients

Soil properties/ Leaf Nutrients	Low (< $\bar{x}$−0.5 SD)	Moderate ($\bar{x}$ ± 0.5 SD)	High (> $\bar{x}$+0.5 SD)
NDVI (Kriged)	37.23	25.65	37.12
NDVI (Ag20/20)	38.42	24.58	37.00
SOM	34.15	29.94	35.92
Soil Fe	33.58	32.77	33.65
EA	34.28	33.94	31.78
Soil pH	31.40	36.32	32.30
NIR absorbance	33.52	34.48	32.01
Chlorophyll index	34.51	32.03	33.46
Leaf Cu	37.65	33.20	29.18
Leaf Mg	34.31	33.79	31.90

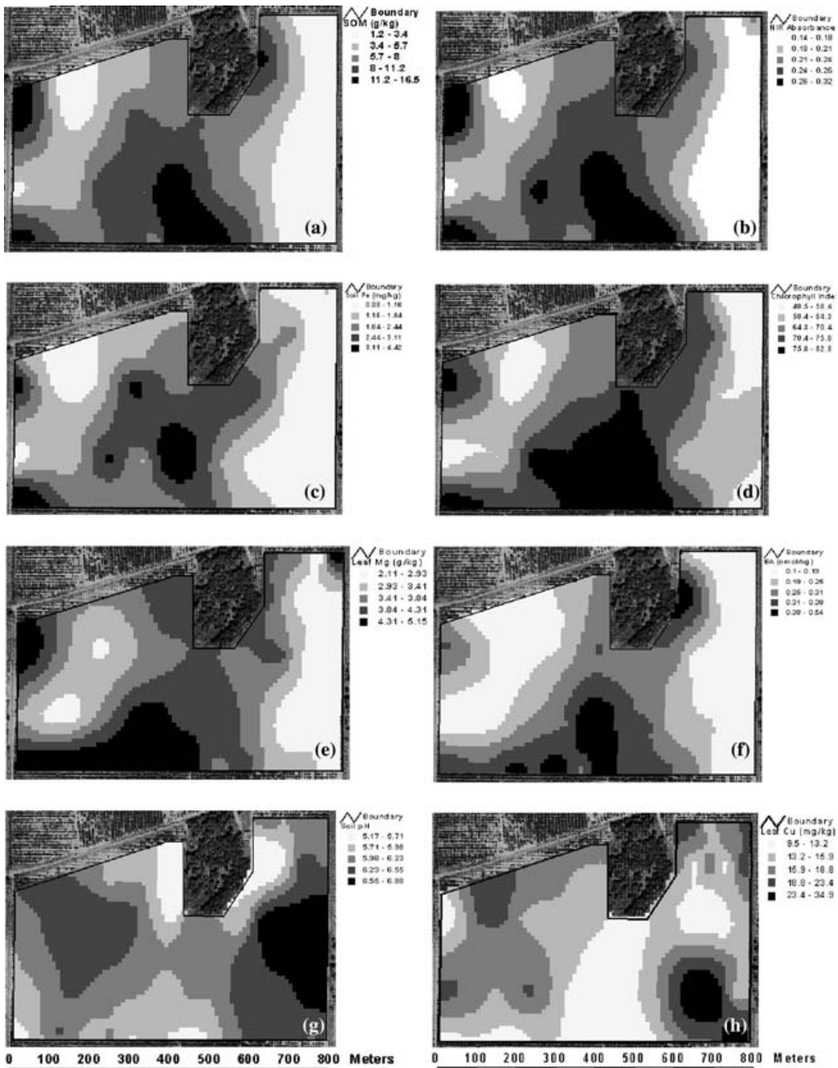

Fig. 4 Maps showing variation in (**a**) SOM (**b**) NIR absorbance (**c**) soil Fe (**d**) chlorophyll index (**e**) leaf Mg (**f**) Ea (**g**) soil pH (**h**) leaf Cu

The kriged maps of NDVI, SOM, soil Fe, NIR, pH, EA, leaf chlorophyll index and leaf Mg showed similar broad gradual and non-random spatial patterns for Revell grove, with significantly different values across the field (Figs. 3a and 4a–g). The high values of NDVI, chlorophyll index, SOM, soil Fe EA, and leaf Mg were located in the north and south central regions of the grove and lower values were found in western and eastern parts of the field. These regions roughly corresponded to the locations of the Zolfo fine sand and Jonathan sand soil series, respectively (Figs. 1 and 4a–e). The NDVI, soil properties and leaf nutrients data show similar overall patterns which largely reflect the differences in the soil associated with the soil series type. However, there was spatial variation within these soil types.

The frequency distribution of kriged data sets was examined and cutoff values representing the mean ± 0.5 standard deviation were used to divide the study site into regions having low ($< \bar{x} -0.5$ SD), moderate ($\bar{x} \pm 0.5$ SD) and high ($> \bar{x} + 0.5$ SD) values of NDVI, soil properties and leaf nutrients (Bhatti et al. 1991). When the data sets were overlaid, the approximately equal percentage of areas for NDVI and selected variables were lying in almost the same regions of the field having low, moderate and high values of these properties (Table 6).

The interpolated NDVI data are useful to divide the study site into regions having low (stunted trees <34.75%), moderate (intermediate trees, 34.75–54.34%) and high (vigorous trees, >54.43%) tree growth (NDVI) within the grove. Approximately 16.83 ha, 11.57 ha, and 16.80 ha of the grove had low, moderate and high values of NDVI, respectively. Low and high tree growth was found largely in Jonathan sand soil and Zolfo fine sand, respectively (Figs. 1 and 3a). The interpolated SOM data are also useful to identify the regions having low (<4.6 g kg^{-1}), moderate (4.6–7.8 g kg^{-1}), and high (>7.8 g kg^{-1}) amounts of organic matter. The same procedure for NDVI cutoff levels was used as described above. Approximately 15.43 ha, 13.53 ha, and 16.24 ha at the study site had low, moderate, and high amounts of soil organic matter, respectively. The poor tree growth (low NDVI) area contained very low organic matter, i.e., corresponding largely to Jonathan sand series (Figs. 1, 3a and 4a). The soils having low organic matter poorly retain water and store and release plant nutrients (Jenkinson 1988). Therefore, low water content and deficiency of essential elements in low organic matter soils could restrict tree growth. Jonathan soils historically have strongly developed and deep E horizons that are severely leached and more nutrient-deficient than Zolfo and Sparr soils (Department of Agriculture-Natural Resources Conservation Service 2001).

The contour map of leaf Cu also showed spatial patterns across the grove but the trend was reversed compared with other variables (Figs. 3a, 4a–h). The trend reversal is due to the negative correlation between leaf Cu and either soil Fe, NDVI or SOM. The correlations between NDVI, soil properties, and leaf nutrients support the relations identified from the maps described above. The excessive Cu was found in the west and eastern parts of the grove, corresponding to the Jonathan soil series (Figs. 1 and 4h). The leaf chlorophyll index values, NDVI, SOM and soil Fe were lower in the parts of the grove having excess Cu (Figs. 3a, 4a, c and h). The shortage of Fe produced by toxic amounts of Cu in Florida sandy, acid and well-drained soils adversely affected the citrus plant growth and production (Smith and Specht 1952). Excessive Cu originates from fungicidal sprays in citrus groves over many years. Stewart and Leonard (1952) discovered that chelated Fe applied to acid soil in small amounts would effectively overcome Fe chlorosis and was a valuable contribution to the solution of the acid-soil chlorosis problem in Florida orchards.

The practical implication of uniformly fertilizing a grove in which substantial areas have widely different sizes of trees is to over-fertilize or under-fertilize large areas of the grove (Schumann et al. 2003). Fertilizer sources could be better managed by developing different management zones for applying variable rates of agrochemicals across the field/grove to better match broad patterns in soil fertility and tree performance (Shanahan and Schepers 2003).

The significant correlation between soil organic matter and either NDVI, soil Fe, EA, leaf Cu, or leaf Mg could be used to make management zones on the basis of (easily measured soil and tree characteristics) either NDVI or SOM variation within grove for the variable application of lime (dolomite) and chelated Fe. The liming, together with the application of chelated Fe, appears to offer fairly satisfactory means of practical control of the undesirable effects of high Cu by raising the pH to 7.0 in most Florida citrus soils

(Reuther and Smith 1953). The basis of dolomite fertilization would be to neutralize Cu toxicity by raising the soil pH and supplying additional Mg to the citrus trees.

Management zones based on spatial variation in (a) NDVI and (b) SOM

The grove was divided into three (low, medium and high) zones (Fig. 5a, b) using the cutoff level procedure reported by Bhatti et al. (1991) on the basis of variation in NDVI and SOM. The low, medium and high tree growth zones averaged NDVI values 22.93, 45.51 and 65.82%, respectively. Tree growth as NDVI in the low, medium and high zones (based on SOM) averaged 22.04, 46.72 and 67.56%, respectively. The SOM, leaf chlorophyll index, soil Fe, EA, leaf Mg and leaf Cu were significantly different between each zone based on NDVI (Table 7) and SOM (Table 8). The dolomite (kg ha^{-1}) and elemental iron requirement for different management zones based on the variation in NDVI and SOM are shown in Fig. 5a, b. The average recommended rates of lime and elemental Fe in low,

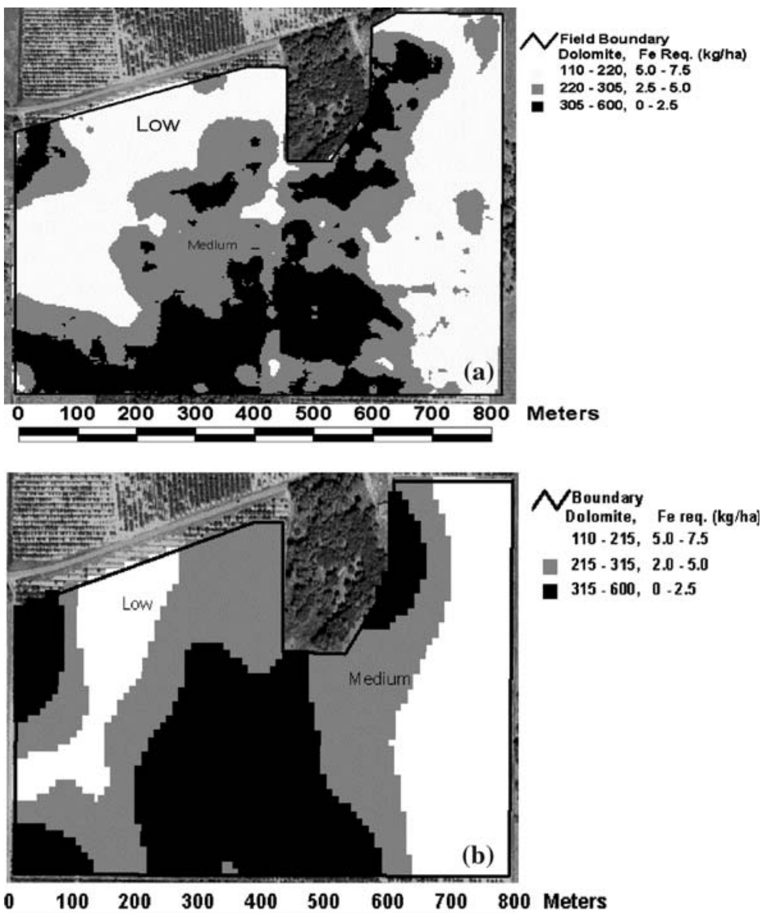

Fig. 5 Management zones and required dolomite and Fe on the basis of spatial variation in (**a**) NDVI (**b**) SOM

Table 7 Comparison of mean NDVI, soil properties, and leaf nutrients for management zones on the basis of NDVI and average required rates of dolomite and elemental Fe for each management zone

Soil properties/Leaf nutrients	NDVI (%) Management Zone		
	Zone 1 <34.75	Zone 2 34.75 –54.34	Zone 3 >54.34
NDVI (%)	22.93[c]	45.51[b]	65.82[a]
SOM (g kg^{-1})	2.9[c]	6.1[b]	9.6[a]
Leaf Cu (mg kg^{-1})	19.01[a]	15.26[b]	12.47[c]
Soil Fe (mg kg^{-1})	0.95[c]	1.84[b]	2.74[a]
Leaf Mg (g kg^{-1})	2.9[c]	4.2[b]	6.3[a]
Chlorophyll index	58.9[c]	67.45[b]	75.77[a]
Soil pH	6.48[a]	6.15[b]	5.83[c]
EA ($cmol^{+}$ kg^{-1})	0.18[c]	0.25[b]	0.33[a]
Dolomite requirement (kg ha^{-1})	200	276	375
Elemental Fe requirement (kg ha^{-1})	6.25	3.75	1.25

Means followed by similar letter(s) in each row not significantly different from each other at the 5% confidence level

Table 8 Comparison of mean NDVI, soil properties, and leaf nutrients for management zones on the basis of SOM and average required rates of dolomite and elemental Fe for each management zone

Soil properties/Leaf Nutrients	Organic Matter (g ha^{-1}) Management Zone		
	Zone 1 <4.6	Zone 2 4.6–7.8	Zone 3 >7.8
SOM (g kg^{-1})	2.8[c]	6.2[b]	10.1[a]
NDVI (%)	22.04[c]	46.72[b]	67.56[a]
Leaf Cu (mg kg^{-1})	19.25[a]	15.06[b]	12.11
Soil Fe (mg kg^{-1})	0.90[c]	1.89[b]	2.84[a]
Leaf Mg (g kg^{-1})	2.9[c]	3.6[b]	4.3[a]
Chlorophyll index	58.50[c]	67.98[b]	76.86[a]
Soil pH	6.50[a]	6.14[b]	5.79
EA ($cmol^{+}$ kg^{-1})	0.17[c]	0.25[b]	0.34[a]
Dolomite requirement (kg ha^{-1})	196	282	390
Elemental Fe requirement (kg ha^{-1})	6.25	3.75	1.25

Means followed by similar letter(s) in each row not significantly different from each other at the 5% confidence level

medium, and high tree growth (NDVI) and SOM zones are also shown in Tables 7 and 8. The advantage of using aerial photography of tree growth for making sampling strategy and management zones is that they are almost the most dense, least expensive of the ancillary data to obtain. The uses of ancillary data have long been advocated in precision agriculture (Whitney et al. 1999; Kerry and Oliver 2003). The second advantage is that the prescription maps for variable rate application of nutrients in each zone within a grove could be reliably and easily generated after calculating the NDVI from aerial photographs of the grove using Ag20/20 extension for ArcView GIS software.

The merit of making the management zones within a grove on the basis of spatial variation in SOM is that the deficiency of Fe and toxic level of Cu in the low SOM zone are both clearly delineated. This allows over-application of Cu to be minimized while correcting the Fe, Mg and lime deficiencies.

Conclusions

- Excessive Cu in the low SOM areas of the grove apparently induced Fe deficiency, visible as chlorotic disorders of the foliage and stunted tree growth.
- The semivariograms for NDVI, soil properties (SOM, soil Fe, NIR, and pH) and leaf variables (chlorophyll index, Cu and Mg) showed strong spatial dependence with large ranges of influence (varied from 230 m to 255 m).
- The spatial variability in selected soil and tree variables within the grove was largely governed by soil type.
- The NDVI and SOM could be used to delineate management zones (low, medium and high) for variable rate application of soil amendments within the grove. The selected soil and plant variables were also significantly different in each management zone (Low, medium and high) based on NDVI and SOM.
- The required amount (kg ha^{-1}) of dolomite and elemental Fe would be calculated for variable rate application in different management zones to improve the tree performance within the grove.

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