RELATIONSHIPS BETWEEN SOIL CHEMICAL STATUS, SOIL NEMATODE COMMUNITY, AND SUSTAINABILITY INDICES[†]

L. Porazinska,[1] R. McSorley,[1] L. W. Duncan,[2] R. N. Gallaher,[3] T. A. Wheaton,[2] and L. R. Parsons[2]

Entomology and Nematology Department[1] and Agronomy Department,[3] University of Florida, Gainesville, FL 32611, and Citrus Research and Education Center,[2] University of Florida, Lake Alfred, FL 33850, U.S.A.

ABSTRACT

Porazinska, D. L., R. McSorley, L. W. Duncan, R. N. Gallaher, T. A. Wheaton, and L. R. Parsons. 1998. Relationships between soil chemical status, soil nematode community, and sustainability indices. Nematropica 28:249-262.

The development of more sustainable agronomic practices will benefit from detailed information on major components of the agroecosystem under various farming schemes. In this study, we focused on the long-term effects of different irrigation levels on the status of several macro- and micronutrients in the soil, and their relationship with the nematode components of the citrus soil ecosystem. In addition, the relationship of chemical (nutrient) and biological (nematode) measures to indices of sustainability was examined. Several soil chemical measures (Ca, Mg, Fe, Zn, and pH) were affected ($P = 0.05$) by water treatments involving different levels of irrigation intensity over time. About 40% of all nematode genera and half of the nematode community indices were significantly correlated with the chemical soil measures. Some of the chemical and nematode indices showed consistent patterns ($P = 0.05$) related to several components of sustainability in citrus agroecosystems (yield, profitability, and water use efficiency). Since the "sustainability indices" reflect different aspects of sustainable agriculture, their usefulness in formulating recommendations requires prioritizing their relative importance. In our experiment, the relationships between omnivorous nematodes, the nematode maturity indices, and water use efficiency, and between irrigation level and profitability allowed us to suggest the optimum irrigation treatment (minimizing water overuse and maximizing profits), and to establish omnivorous nematodes and the nematode maturity indices as indicators of water management history.

Key words: agricultural practices, bioindicators, citrus ecosystem, Florida, irrigation, nematode community, soil ecology, soil minerals, sustainable agriculture.

RESUMEN

Porazinska, D. L., R. McSorley, L. W. Duncan, R. N. Gallaher, T. A. Wheaton y L. R. Parsons. 1998. Relación entre el estado químico del suelo, la comunidad de nematodo del suelo, y los índices de sustentabilidad. Nematrópica 28:249-262.

El desarrollo de prácticas agronómicas más sostenibles se beneficiará con una información más detallada de los principales componentes del ecosistema agronómico bajo diferentes sistemas agrícolas. En este estudio nos concentramos en los efectos del uso a largo plazo, de diferentes niveles de irrigación en el estado de varios macro- y micronutrientes del suelo y su relación con los nematodos componentes del ecosistema cítricos-suelo. Además, se examinó la relación de la medición de los elementos químicos (nutrientes) y biológicos (nematodos) a los índices de sustentabilidad. Varias mediciones químicas del suelo (Ca, Mg, Fe, Zn, y pH) fueron afectadas ($P = 0.05$) por los tratamiento con agua, a diferentes intensidades de irrigación en el tiempo. Alrededor del 40% de todos los géneros de nematodos y la mitad de los índices comunitarios de nematodo, estuvieron significativamente correlaciona-

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dos con las mediciones químicas del suelo. Algunos de los índices químicos y de nematodos mostraron modelos consistentes ($P = 0.05$) en relación a varios componentes de sustentabilidad en agroecosistemas de cítricos (rendimiento, ganancia, y eficiencia del uso de agua). Debido a que los "índices de sustentabilidad" reflejan diferentes aspectos de la agricultura sostenible, su utilidad en la formulación de recomendaciones requiere priorizar su importancia relativa. En nuestro experimento, las relaciones entre nematodos omnívoros, los índices de maduración de nematodo, y la eficiencia del uso de agua, y entre el nivel de irrigación y la ganancia, nos permitieron sugerir el tratamiento óptimo de irrigación (minimizando el uso de agua excesivo y aumentando las ganancias), y establecer los nematodos omnívoros y el índice de maduración de nematodo como indicadores de la historia del manejo de agua.

Palabras claves: agricultura sostenible, bioindicadores, comunidad de nematodo, ecología del suelo, ecosistema de cítricos, Florida, irrigación, minerales del suelo, prácticas agriculturales.

INTRODUCTION

Agricultural management practices affect soil characteristics. Reduction in diversity of soil biota (Paoletti *et al.*, 1992), loss of soil organic matter content, and increased soil erosion (Ehrlich, 1988) are problems in many conventional agricultural systems. Other effects of farming systems that use high amounts of matter and energy (fertilizers, pesticides, irrigation, and cultivation) are ground and surface water contamination, leading to potential hazards to human and animal health (Schaller, 1993). The above problems, along with a rapidly diminishing supply of natural resources, have forced many scientists and farmers to seek more sustainable and environmentally sound methods for food and fiber production.

Over the last decade, sustainable agriculture has become a new paradigm for the future of agriculture (Kenneth *et al.*, 1996; Schaller, 1993). Recently, much effort has been devoted to defining chemical and biological indicators that can be useful in recognizing sustainable systems (Doran and Safley, 1997). A problem with this approach is in the definition of a sustainable agricultural system. Although many people use the term, the understanding of "sustainable agriculture" may vary from one person to another. For most people, however, sustainable agriculture symbolizes conservation of natural resources and protection of the environment as well as production of adequate amounts of food and profits for farmers, on a longtime scale (future generations).

It has been argued that the preceding definition is too broad and lacking in scientific precision (Schaller, 1993). The very nature of any agroecosystem, characterized by a nearly infinite number of variables, implies that sustainability can be defined in terms of many possible variables or combinations of variables. These include items such as conservation of biodiversity, levels of specific pollutants and other chemicals, conservation of water and other natural resources, grower profits, adequate yield levels, and the like. Moreover, attempts to increase sustainability with regard to some variables may conflict with others. For example, in many regions conservation of water is desirable for future generations, but may conflict with current production practices which reduce the area under cultivation by increasing crop yields.

From the practical point of view, farmers would not likely choose to maximize either water conservation or yield, but rather the profitability of production practices. Moreover, because of market competition, the most profitable practices will be the most sustainable ones for a given set of economic conditions. Profitability could include broad aspects of the agroecosystem (e.g. hidden management costs such as cost of environmental remediation, projected future values of limited resources, estimated value of biodiversity, etc.), and thereby provide a reasonable index of sustainability by revealing the optimum relationship between crop production and management inputs (Duncan and Noling, 1998). However, it is currently more feasible to restrict this definition to grower profits, and in the present study we focus on profitability and resource use efficiency (water).

In Florida citrus orchards, irrigation is one of the most important management tactics to increase fruit yield (Jackson *et al.,* 1995). Typical Florida soils, with very high sand content and extremely low moisture holding capacity, are exposed to constant excessive drying under conditions of relatively high temperatures. Because irrigation generally increases fruit yield, farmers may choose to apply higher than necessary amounts of water to ensure their economic returns. Irrigation also affects the condition of the soil ecosystem (nutrient and pesticide loss through leaching, accumulation of metals, shift in microbial community structure, etc.). Detailed analysis of both chemical and biotic components of the soil ecosystem under various watering regimes can provide information about key variables (concentrations of nutrients, heavy metals, soil organic matter content, biodiversity, etc.) that define the conditions of the soil environment. Resulting information on the soil ecosystem status may permit farmers to better manage water resources. As a biological component of the ecosystem, nematode community structure should tend to integrate physical and chemical characteristics of the environment (Cairnes *et al.,* 1993). Because nematodes are ubiquitous to all habitats and present a variety of feeding habits (algal-, bacterial-, fungal-feeders, omnivores, plant parasites, predators, root associates) and life strategies (r-K), they have been increasingly suggested as potential indicators of the status of the soil ecosystem. Nematodes have been proposed as good indicators of productivity, pollution, secondary succession, and disturbance (Bongers *et al.,* 1991; Ferris *et al.,* 1996; Freckman and Ettema, 1993; McSorley and Frederick, 1996; Wasilewska, 1994; Yeates, 1994; Yeates and Bird, 1994). Nematodes have also been proposed as useful in defining sustainable agroecosystems (Neher and Campbell, 1994).

The effects of soil nutrients on yields have been investigated routinely in agricultural sciences. Fewer attempts, however, have been made to look at the effects of farming practices on soil chemistry and its relationships with nematode community patterns. The objective of this study was to evaluate the long-term effects of various irrigation intensities on the nematode community and the status of several macro- and micronutrients in the soil. To validate the usefulness of nematodes as bioindicators of the soil ecosystem status, relationships between these nutrients and nematode genera and nematode community indices were investigated. In addition, we investigated nematode community measures in the context of several aspects of sustainability, described here by three indices: yield, water use efficiency, and profitability.

MATERIALS AND METHODS

Experimental design. The experiment was carried out at the University of Florida, Citrus Research and Education Center (CREC), Lake Alfred, Florida. The soil was an Astatula fine sand with an average pH of 6.2 and 0.7% organic matter. For the last 80 years, the research site had been planted to citrus *(Citrus* spp.) trees. On 10 April, 1991, young (approximately 1-year-old) citrus trees of 'Hamlin' orange (*Citrus* *sinensis* (*L.*) Osbeck) on 'Swingle' citrumelo (*Citrus paradisi* × *Poncirus trifoliata*) rootstock free of endoparasitic nematode pests were planted in rows 6.1 m apart, with 3.9 m between trees in rows. The irrigation treatments began on 1 June, 1991, but the data presented here begin from the fourth year (1995) after establishment of the experiment. During 1991 to 1996, nutrient management followed the fertilizer guidelines typical for citrus in Florida (Ferguson *et al.,* 1995). For weed control under the tree canopies, the herbicide glyphosate was applied as necessary (3 to 4 times per year at approximately two-month intervals beginning in late February or early March). Fertilizer and herbicide rates were applied equally to all treatments.

Trees were watered at six different irrigation intensities every fourth day. Irrigation intensities were expressed as a proportion of the average evapotranspiration rate (ET): 0.43 ET, 0.57 ET, 0.85 ET, 1.00 ET, 1.32 ET, and 1.95 ET. These proportions were achieved by using different size microsprinkler openings in the irrigation system. The amount of water required for each month was calculated from the measurements of historical ET. For instance, if ET for January of the previous 70 years was 0.18 cm of water per day, the treatment 1.00 ET would receive 0.72 (0.18 cm × 4 days) cm of water every fourth day in January. Other treatments would receive an assigned proportion of that amount (e.g. 0.43 ET would receive 0.72 × 0.43 = 0.31 cm of water every fourth day). The monthly ET typically varies from a low of 0.18 cm/day for January to a high of 0.46 cm/day of water in May.

The experiment was arranged in a randomized complete block design with four blocks, each with one replication. Soil samples were collected in May and October, 1995, and February and May, 1996. Each soil sample was a bulk of 16 soil cores (2 cm in diameter, from 0-30 cm soil depth) taken in a diagonal transect pattern under the tree canopy. Each soil sample was passed through a sieve (2 mm × 2 mm mesh size) to separate the soil from root tissue. Samples from each sampling date were processed for nematode analysis. Samples collected on 10 February, 1996 were also processed to determine soil moisture, density of pathogenic fungi, citrus fibrous root density and soil chemical status.

Biological measures. A subsample of approximately 100 cm^3 soil was immediately used to estimate propagule densities of *Phytophthora nicotianae,* a fungal pathogen of citrus roots (Timmer *et al.,* 1988). Nematodes were extracted from another 100 cm^3 soil subsample by wet sieving followed by centrifugation (Jenkins, 1964). Extracted nematodes were killed with heat, counted, and identified mostly to genus. Based on nematode community data, ecological indices such as fungivore to bacterivore ratio (Freckman and Ettema, 1993), fungivores plus bacterivores to plant parasites ratio (Wasilewska, 1994), richness (number of genera), trophic dominance (Simpson, 1949), trophic diversity (Shannon and Weaver, 1949), maturity index (Bongers, 1990), and total maturity index (Yeates, 1994) were calculated. Additional background and detailed procedures for calculation of these indices are presented elsewhere (Porazinska *et al.,* 1998). Separated roots were washed, dried at 60°C, and weighed.

Chemical measures. A separate soil subsample of approximately 100 cm^3, collected in February 1996, was air-dried and used to determine various soil chemical measures. Mehlich I extractable Ca, Mg, K, Na, P, Cu, Fe, Mn, and Zn (Mehlich, 1953) as well as N, pH, buffer pH, soil organic matter (SOM), and cation exchange capacity (CEC) were determined. Calcium, Mg, Cu, Fe, Mn, and Zn concentrations in soil extracts were determined by atomic absorption spectrophotometry. Potassium and Na were resolved by atomic emission spectrophotometry using a Perkin-Elmer Atomic Absorption Spectrophotometer. Concentrations of P were estimated by colorimetry. Soil water pH was evaluated from 20 ml of soil suspended in 40 ml of deionized water. The pH measurements were taken 30 minutes after stirring, with a calibrated pH-meter. Soil organic matter was estimated by placing 1 g of soil in a 500-ml Erlenmeyer flask, adding 10 ml of 1 N K_2SO_4 and mixing by gentle rotation for about one minute. The mixture was diluted with deionized water to 200 ml after 30 minutes, and 5 drops of an indicator were added. The suspension was titrated with 0.5 N $FeSO_4$ until the dull green color of the solution changed to a reddish brown. A soil sample with a known organic matter content was utilized as a check sample (modified procedure of Jackson, 1958 and Horwitz, 1975). CEC was determined by cation summation (Jackson, 1958). An aluminum digest block was used to capture N in soil extract (Gallaher *et al.,* 1975). A Technicon Autoanalyzer II was used to determine concentrations of N (N was trapped and recorded as $(NH_4)_2SO_4$).

Sustainability measures. For practical reasons, we chose yield, water use efficiency, and financial profitability as measures of different aspects of sustainability. Because the trees had not reached productive maturity, the yield data were presented in three forms: separate fruit production for 1995 and 1996, and 1995 and 1996 data pooled into one fruit yield value to better illustrate tree fruit productivity. Water use efficiency (kg/cm), which expresses yield per centimeter of irrigation water applied, was derived from the yield (kg/ha) data divided by the amount of water used in a particular treatment (cm/ha). Profitability was based on a typical cost-benefit analysis used by farmers. Costs were estimated using budget tables created by Muraro (1997). All cost factors were constant across irrigation treatments, except fuel cost for irrigation pumps, which varied in proportion to the six water treatment levels. We assumed a price for a box of fruit (40.9 kg) to be $5.60, which is a current price for early orange varieties (Muraro, 1997).

Statistical analysis. Relationships between irrigation intensity and soil chemical properties, nematode community measures, *Phytophthora nicotianae* populations, root biomass, and soil moisture on 10 Feb, 1996, were derived using correlation analysis. Selected relationships were further examined using analysis of variance and orthogonal contrasts procedures. All statistical computations were performed utilizing SAS software (SAS Institute, Inc., Cary, NC). Selected relationships involving nematode measurements or indices were also examined using data from the remaining sampling dates.

RESULTS AND DISCUSSION

Chemical measures. The data presented here begin from the fourth year of the experiment, and thus should reflect the long-term effects of different irrigation rates on the soil chemistry. A significant ($P = 0.05$) positive correlation with the irrigation rate was found for Ca, Mg, Zn, pH, and buffer pH (BpH) ($r = 0.48$ for Ca, $r = 0.56$ for Mg, and $r = 0.48$ for Zn) (Tables 1-2). While Fe was not correlated with the irrigation rate, the orthogonal contrasts procedure revealed that the highest concentrations of Fe were associated with treatments receiving the lowest amounts of water (0.57, 0.43 ET) and were significantly higher ($P = 0.05$) than Fe concentrations in treatments with the four higher water rates.

Table 1. Soil chemical measures obtained from soil beneath citrus trees exposed to six different irrigation intensities expressed as a proportion of the evapotranspiration rat (ET) (0.43, 0.57, 0.85, 1.00, 1.32, and 1.97 ET) on 10 February 1996. The concentrations of soil minerals are in mg/kg^{-1}.

	Irrigation intensity					
Measurement[y]	0.43 ET	0.57 ET	0.85 ET	1.00 ET	1.32 ET	1.97 ET
Ca	262 ± 85[z]	271 ± 76	224 ± 59	278 ± 110	289 ± 49	397 ± 121
Mg	19.4 ± 3.7	21.4 ± 2.1	22.1 ± 5.8	20.3 ± 2.7	25.5 ± 4.1	27.2 ± 5.1
K	13.0 ± 3.8	12.3 ± 2.5	12.2 ± 2.3	9.4 ± 1.3	12.2 ± 3.5	10.7 ± 0.7
Na	22.1 ± 4.0	18.6 ± 3.2	17.0 ± 1.5	19.6 ± 4.5	18.0 ± 0.8	19.7 ± 4.2
N	274 ± 15	296 ± 58	290 ± 67	243 ± 11	287 ± 50	296 ± 23.4
P	91.3 ± 28.6	81.6 ± 30	53.2 ± 8.1	87.2 ± 42.5	57.6 ± 7.2	91.7 ± 34.2
Cu	16.5 ± 6.8	14.6 ± 4.4	15.7 ± 8.0	16.4 ± 6.7	15.2 ± 2.9	15.8 ± 3.7
Fe	19.2 ± 1.5	17.1 ± 1.7	15.4 ± 2.9	15.7 ± 0.8	15.0 ± 1.7	16.6 ± 0.5
Mn	10.16 ± 1.79	9.10 ± 1.3	9.24 ± 2.2	8.70 ± 3.3	8.85 ± 1.3	9.44 ± 0.9
Zn	3.88 ± 2.1	5.08 ± 2.4	4.44 ± 1.7	4.69 ± 2.4	5.62 ± 1.0	6.96 ± 1.2
pH	5.45 ± 0.1	5.95 ± 0.2	6.10 ± 0.3	6.30 ± 0.4	6.38 ± 0.1	6.68 ± 0.3
BpH	7.88 ± 0.1	7.93 ± 0.1	7.93 ± 0.1	7.95 ± 0.1	7.95 ± 0.1	7.97 ± 0.1
CEC	2.56 ± 0.5	2.25 ± 0.3	1.95 ± 0.7	2.05 ± 0.7	2.17 ± 0.5	2.59 ± 0.7
OM	0.62 ± 0.1	0.70 ± 0.1	0.60 ± 0.3	0.52 ± 0.1	0.38 ± 0.3	0.84 ± 0.3

[y] BpH = buffer pH, CEC = cation exchange capacity in meq/100 g, OM = organic matter in %.

[z] Data represents means ± standard deviations of four replicates.

Soil pH was positively correlated with the increase of irrigation intensity ($r = 0.79$, $P = 0.05$) (Tables 1-2). In the lowest water rate treatment, the soil was slightly acidic and pH steadily increased until reaching almost neutrality in the treatment receiving the highest amount of water. Irrigation intensity was also positively correlated with buffer pH ($P = 0.05$, $r = 0.64$).

Various water level treatments affected only some soil chemical measurements. For example, the shift of Ca and Mg concentrations in the soil with the water rate increase can be explained by Ca and Mg present in the irrigation water derived from subsurface wells in soil horizons rich in limestone and dolomites (Brown *et. al.*, 1991). High levels of Ca and Mg in soil help to keep soil pH close to neutral. Increasing soil pH to slightly below 7 has been associated with consistent and significant citrus yield improvements (Hanlon *et al.*, 1995; Jackson *et al.*, 1995).

Accumulation of Zn in the soil may pose a toxicity threat to citrus trees. Interestingly, in our experiment, total concentration of Zn increased as more water was applied (higher pH). Generally, in situations of high Cu, Mn, or Zn levels, additions of higher Ca amounts should suffice to control the available levels of these heavy metals in the soil. Declining Fe levels with irrigation elevation suggest that either Fe became unavailable due to higher pH levels or Fe was leached to the deeper layers of the soil profile.

Table 2. Correlation coefficients between soil chemical measures, and nematode genera and community indices.

Measurement^x	Ca	Mg	K	Na	N	P	Cu	Fe	Mn	Zn	pH	BpH	CEC	% SOM
BACTERIAL FEEDERS														
Acrobeloides	—	—	0.459**^{y}	—	—	—	—	0.409**	—	—	-0.390*	-0.368*	—	—
Cephalobus	—	—	0.402**	—	—	—	—	—	—	—	—	—	—	—
Eucephalobus	—	-0.453**	—	—	—	—	—	—	—	—	-0.491**	-0.501**	—	—
Plectus	0.414**	0.472**	—	—	—	—	—	—	—	—	0.437**	—	—	—
Prismatolaimus	—	—	—	0.364*	—	—	—	0.537**	0.355*	—	-0.553**	-0.537**	—	—
Wilsonema	—	0.436**	—	—	—	—	—	—	—	—	0.456**	0.502**	—	—
FUNGAL FEEDERS														
Aphelenchoides	—	—	—	—	—	—	—	0.492**	—	—	—	—	—	—
OMNIVORES														
Eudorylaimus	0.413**	0.485**	—	—	—	—	—	—	—	0.387*	—	—	—	—
Aporcelaimellus	—	—	—	—	—	—	—	—	0.368*	0.381*	0.368*	0.381*	—	—
ROOT ASSOCIATES														
Tylenchus	—	—	0.543**	—	—	—	—	—	—	—	—	—	—	-0.425**
PLANT PARASITES														
Belonolaimus	—	-0.433**	—	—	—	—	—	—	—	—	-0.377*	—	—	—
Criconemoides	—	0.379*	—	—	0.503**	—	0.522**	—	0.424**	0.423**	—	-0.453**	0.490**	—
Total	—	—	0.367*	—	—	—	—	—	—	—	—	—	—	—

Table 2. (Continued) Correlation coefficients between soil chemical measures, and nematode genera and community indices.

Measurement[x]	Ca	Mg	K	Na	N	P	Cu	Fe	Mn	Zn	pH	BpH	CEC	% SOM
Bacterivores	—	—	0.375*	—	—	—	—	—	—	—	—	—	—	—
Fungivores	—	—	—	—	—	—	0.371*	—	0.345*	—	—	—	—	—
Omnivores	0.353*	0.391*	—	—	—	—	—	—	—	—	0.424**	0.421**	—	—
B/F	—	—	0.363*	—	—	—	—	—	—	—	—	—	—	—
B/T	—	-0.456**	—	—	—	—	—	—	—	—	—	—	—	—
(B + F)/T	—	—	—	—	—	—	—	—	—	—	—	—	—	0.418**
O/T	0.366*	—	—	—	—	—	—	—	—	—	0.435**	0.423**	—	—
H_2O	—	0.489**	—	—	—	—	0.391*	—	—	—	0.403*	—	—	—
Richness	—	0.353*	—	—	—	—	—	—	—	—	—	—	—	—
Trophic div.	—	0.442**	—	—	—	—	—	—	—	—	—	—	—	—
Trophic dom.	—	-0.448**	—	—	—	—	—	—	—	—	—	—	—	—
ΣMI	—	0.478**	—	—	—	—	—	—	—	—	0.362*	—	—	—
MI	0.369*	0.359*	—	—	—	—	—	—	—	—	—	—	—	—
Irrigation[z]	0.484**	0.560**	—	—	—	—	—	—	—	0.476**	0.793**	0.640**	—	—

[x] BpH = buffer pH, CEC = cation exchange capacity, SOM = soil organic matter, B/F = bacterivorous to fungivorous nematode ratio, B/T = proportion of bacterivorous nematodes in the nematode community, trophic div. = trophic diversity, trophic dom. = trophic dominance (Freckman and Ettema, 1994), ΣMI = maturity index (Yeates, 1993), MI = maturity index (Bongers, 1990).

[y] **Statistically significant at $P \leq 0.05$, *statistically significant at $P \leq 0.10$.

[z] Irrigation intensity as proportion of evapotranspiration rate.

Lack of consistent patterns for P and N in relation to water regimes probably can be explained by high immobility of P in the soil (Paul and Clark, 1989), and by the N management practice which involves 6 to 7 applications of this fertilizer per year (Ferguson *et al.,* 1995). The very low soil organic matter reflected the extremely high sand content (up to 98%) and continuous control of weeds by herbicides under the tree canopy. Only a small fraction of plant debris reaches the soil surface and thus limits the possibilities for soil organic matter formation.

Biological measures. Population density of P. *nicotianae* and root biomass did not have any linear relationship with soil nutrients (data not shown). Only 30-40% of all nematode genera and half of the nematode community indices were significantly correlated with the chemical elemental levels (Table 2). *Acrobeloides, Cephalobus,* and *Eucephalobus* (bacterial feeders) belong to the same nematode family (Cephalobidae); however, they responded differently to soil chemical characteristics, indicating their preferences for different soil microhabitats. Moreover, the implications of the correlations are unclear. The extent of ecological knowledge on bacterivorous nematodes is still very limited and requires further investigation. At this stage of knowledge, it would be unwise to suggest bacterivores as definite or dependable indicators of sustainability attributes in this agroecosystem.

Among the plant parasites, *Belonolaimus longicaudafus* can cause severe problems on citrus trees (Duncan *et al., 1996*). From the economic perspective, information about this nematode is of particular interest. Densities of *Belonolaimus* were negatively correlated with pH and Mg concentrations and are thus related to the irrigation rate. Whether population density is regulated by water, chemical properties or a hidden variable is unknown.

The majority of omnivorous nematodes are K-strategists (long life cycle, low reproductive rate, few offspring, stable habitats), therefore they are believed to be sensitive to environmental stressors (Bongers, 1990). The presence of high numbers of omnivores in the soil should indicate stable soil systems. Population densities of the omnivore genera *Eudorylaimus,* and *Aporcelaimellus,* total numbers of omnivores, and the ratio of omnivores to total abundance (O/T), all showed similar patterns, usually favoring high pH, BpH, and high Ca and Mg concentrations. Since these measures were highly correlated with the irrigation intensity (Porazinska *et al.,* 1998), it would be interesting to investigate the nature of this relationship in more detail. Relatively high correlations of *Eudorylaimus* and *Aporcelaimellus* with Zn and Mn concentrations suggest that these metals may be far from approaching any toxic concentration levels and thus control of micronutrient availability by liming is unnecessary.

Maturity index (MI) and total maturity index (ΣMI) (Bongers, 1990; Yeates, 1994) were related to many of the same variables as omnivorous nematodes. This response was expected since an increase of MI and ΣMI values usually results from higher proportions of omnivores in the nematode community.

A useful bioindicator of environmental status should probably be responsive to a wide range of factors. In the current study, the nematode genera showing significant correlations with the most chemical elements were *Criconemoides* (5 elements), *Eudorylaimus* (3 elements), *Plectus* (2 elements), *Prismatolaimus* (3 elements), and *Wilsonema* (3 elements). Of all the factors measured (Table *2), Criconemoides* was correlated with 7, *Prismatolaimus* with 5, and *Acrobeloides, Aporcelaimellus,* and total omnivores with 4 each.

Sustainability measures. In general, higher irrigation levels positively influenced citrus tree fruit production (Fig. 1). Profitability estimates indicated that 1996 was the first year of monetary gains in this citrus orchard. This is a rather typical scenario because it takes about 7-10 years for a citrus tree to reach its productive maturity. Cumulative profitability suggested that the biggest financial losses were associated with the lowest water treatments (Fig. 2). However, greater than 0.85 ET irrigation levels did not contribute to minimization of those losses. In 1996 we observed a similar trend, with the 0.85 ET levels as the most profitable water treatment. Therefore, a slightly greater yield recovery from treatments higher than 0.85 ET water levels did not justify the additional management (irrigation) expenses. This would be even more obvious if a minimal price of water was added to the management costs (e.g. 0.0002 cent/L), under which scenario the 0.85 ET treatment is the only profitable one. As suspected, water use efficiency was lowest in treatments receiving the greatest amounts of water, indicating poor water conservation efforts at the higher rates (Fig. 3).

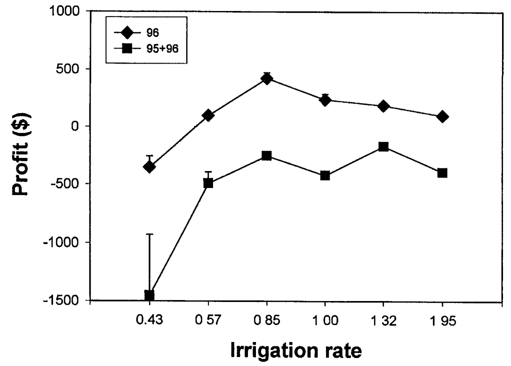

Fig. 2. Relationship between irrigation rate (0.43 ET, 0.57 ET, 0.85 ET, 1.00 ET, 1.32 ET, and 1.95 ET) and profitability ($) for 1996, and 1995 and 1996 pooled together. ET = evapotranspiration. Standard deviations represented by error bars.

Only few nematodes revealed relationships with all the measures of sustainability presented here (Table 3). *Prismatolaimus,* an unusual bacterivore (K-strategist), seems to be particularly interesting, indicating several aspects of sustainability at the same time. From an economic standpoint (here represented by yield and profitability), treatments with lower densities of *Prismatolaimus* (higher water rates) appear favorable, whereas treatments pro-

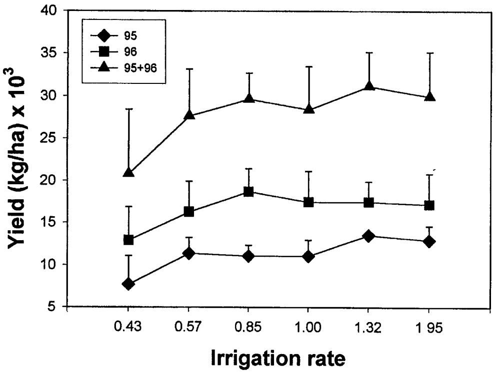

Fig. 1. Relationship between irrigation rate (0.43 ET, 0.57 ET, 0.85 ET, 1.00 ET, 1.32 ET, and 1.95 ET) and the yield (kg/ha) for 1995, 1996, and the cumulative yield (1995+1996). ET = evapotranspiration. Standard deviations represented by error bars.

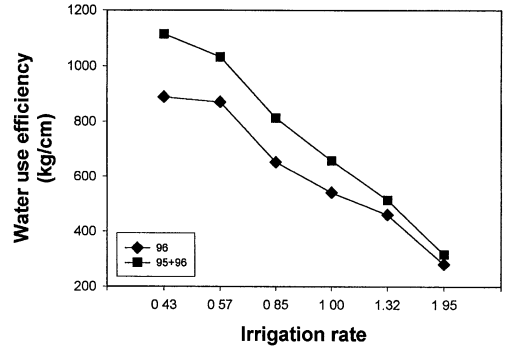

Fig. 3. Relationship between irrigation rate (0.43 ET, 0.57 ET, 0.85 ET, 1.00 ET, 1.32 ET, and 1.95 ET) and water use efficiency (kg of yield per cm of applied water) for 1996, and 1995 and 1996 pooled together. ET = evapotranspiration. Standard deviations represented by error bars.

Table 3. Correlation coefficients between chemical and biological measures and indices of sustainability.

Measurement[y]	Yield (1996)	Yield (1995 + 1996)	Water use efficiency (1996)	Water use efficiency (1995 + 1996)	Profitability (1996)	Profitability (1995 + 1996)
Ca	—	—	-0.420**[z]	-0.410**	—	—
Mg	—	0.425**	-0.525**	-0.507**	—	0.364*
Na	-0.427**	-0.402*	—	—	-0.442**	-0.432**
P	—	—	—	—	-0.355*	—
Fe	-0.650**	-0.645**	0.432**	0.421**	-0.638**	-0.659**
Zn	—	—	-0.435**	-0.416**	—	—
pH	0.642**	0.763**	-0.822**	-0.806**	0.545**	0.698**
BpH	0.602**	0.689**	-0.682**	-0.666**	0.530**	0.645**
Monhysterida	-0579**	-0.522**	0.374*	0.368*	-0.553**	-0.555**
Eucephalobus	-0.480**	-0.521**	0.498**	0.497**	-0.427**	-0.487**
Prismatolaimus	-0.471**	-0.529**	0.412**	0.389**	-0.436**	-0.518**
Wilsonema	—	—	-0.440**	-0.437**	—	—
Eudorylaimus	—	—	-0.424**	-0.413**	—	—
Belonolaimus	—	-0.480**	0.470**	-0.405**	—	-0.444
Omnivores	—	—	-0.407**	-0.405**	—	—
B/T	—	-0.371*	—	—	—	-0.371*
(B + F)/T	—	—	—	0.382*	—	—
O/T	—	—	-0.487**	-0.489**	—	—
H_t	—	0.363*	—	—	—	0.347*
λ_t	—	-0.368*	—	—	—	-0.367*
ΣMI	—	—	-0.479**	-0.466**	—	—
MI	—	—	-0.406**	-0.400*	—	—
Soil moisture	—	0.379*	-0.440**	-0.426**	—	0.350*

[y] BpH = buffer pH, B/T = proportion of bacterivorous nematodes in the nematode community, (B + F)/T = proportion of bacterivorous and fungivorous nematodes in the nematode community, O/T = proportion of omnivorous nematodes in the nematode community, H_t = trophic diversity, λ_t = trophic dominance, ΣMI = total maturity index, MI = maturity index.

[z] **Statistically significant at $P \leq 0.05$, *statistically significant at $P \leq 0.10$.

ducing highest densities of *Prismatolaimus* contribute to water conservation. Very similar relationships were observed for *Eucephalobus* spp., and *Belonolaimus.*

In contrast, omnivores, % omnivores, MI and ΣMI exhibited inverse relationships with water use efficiency. By virtue of representing broad groups of species, these latter categories are likely to be more robust indicators of environmental status because, unlike individual species, they can be estimated from all soil samples. Indeed, % omnivores, MI and ΣMI were also inversely related ($P < 0.05$) to water use efficiency on each of the other sampling dates. The mean (and standard error) correlation coefficient for % omnivores, MI and ΣMI with water use efficiency (1995 and 1995 + 1996) for all sampling dates were -0.61 (0.05), -0.53 (0.03), and -0.53 (0.04), respectively. No other community index, nor any single species was so closely related to water use efficiency, considering the magnitude of correlation coefficients or the number of dates on which the relationship was significant.

In this study, different irrigation treatments were required to maximize either water use efficiency or profitability. Consequently, biological indices revealed the status of one or the other sustainability index, or alternated between positive and negative correlations for one or the other. Because irrigation directly affects the soil ecology, it is not surprising that the biological indices were more reflective of water use efficiency (irrigation rate) than profitability. Nevertheless, agricultural systems are more or less sustainable based on profitability as well as on resource availability and management. Developing rational management practices will require prioritizing these requirements. Water use efficiency should have a higher social priority than profitability in regions where natural recharge of water does not exceed its use. Various means (water surcharges, water use restrictions, etc.) are available to society to increase water use efficiency in agricultural and other endeavors. However, it is desirable to use these means judiciously because they come at a cost to society in the form of higher food prices. For this reason, profitability that includes not only production but also "environmental" costs, remains an important consideration when prioritizing factors related to agricultural sustainability.

Conclusions: Information on the relationships between the irrigation regimes and the soil chemical status and the nematode community illustrates important aspects of the soil condition. In terms of water conservation, several chemical and nematode indices reflected some of the soil conditions (treatments receiving greater amounts of water) of this ecosystem. No relationships between the majority of nematode indices and profitability were revealed, indicating that this condition of sustainability often has little biological basis. Since yield, water use efficiency, and profitability reflect different aspects of sustainable agriculture, they may conflict with respect to optimum management practices. In our experiment, however, based on the revealed relationship between K-strategists and water use efficiency, and that between irrigation level and profitability, we could tentatively suggest 0.85 ET as the best soil water regime for most components of sustainable agriculture, and omnivorous nematodes as the most useful indicators of water management history.

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