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A comparison of indexing methods to evaluate quality of horticultural soils. Part II. Sensitivity of soil microbiological indicators

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Abstract. Soil is a non-renewable natural resource, considered as the basis for food production. Changes in soil properties may indicate potentially beneficial or degradative effects of a given management practice, so it is important to select the most sensitive soil properties to act as quality indicators. This research evaluated different approaches to selecting soil quality indicators in the construction of soil quality indices (SQIs). The sensitivity of integrative SQIs, constructed by considering diverse chemical, physical, and biological properties, was compared with biological SQIs, using only biochemical and microbiological indicators, to assess soil quality in an intensive horticultural production system under short- and long-term organic and conventional management. The results provided by the SQIs showed that plots under organic management had increase soil quality compared with the conventionally managed plots, independent of the number of years under production. The SQIs integrated by physical, chemical and biological indicators were more sensitive than indices composed only of biological indicators, as they did not reflect the physical properties of the studied plots. The organic amendments had a great influence on the microbial community; therefore, microbiological indices could not provide reliable information on soil quality in production systems with high inputs of organic materials.

Additional keywords: catabolic response profiles, phospholipid fatty acid profiles.

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Introduction

The growing global demand for food must be accompanied by minimal degradation of soil quality; this is a significant challenge for both agricultural and environmental sciences. Intensive horticultural production is one of the main activities in the green belt around Buenos Aires city, Argentina (González *et al*. 2010). Conventional horticultural farming is dependent on intensive use of pesticides and fertilisers, leading to deterioration of soil physical, chemical and biological properties (Ge *et al*. 2011). Problems associated with conventional agricultural management have led to the development and promotion of organic farming practices that address environmental and public health concerns (Melero *et al*. 2006).

Soil quality is considered a key element of sustainable agriculture and commonly defined as ‘the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation’ (Karlen *et al*. 1997). A better knowledge of soil quality is important to improve sustainable land use management and provide early warning signs of adverse trends (Bindraban *et al*. 2000; McGrath and Zhang 2003). Changes in soil properties may indicate potentially beneficial or degradative effects of a given management practice (McCool *et al.* 2008), so it is relevant to select the most sensitive soil properties to act as quality indicators. Sets of soil quality indicators have been proposed (Larson and Pierce 1994; Doran and Parkin 1994; Karlen *et al.* 1998), with soil quality evaluated based on the total dataset indicator method. Also, representative indicators have been suggested, e.g. the minimum dataset, selected according to correlation between indicators and ease of measurement (Andrews *et al.* 2002*a*; Raiesi 2006; Govaerts *et al.* 2006), and the Delphi dataset (Zhang *et al.* 2004), selected according to the importance of the indicators to soil quality based on the opinion of experts

(Herrick *et al.* 2002). Soils of the world present many competing uses and inherent limitations, so the components of a minimum dataset are not universal, and these 'sets' may vary from location to location depending on land use, soil function, or soil-forming factors. Improving the existing methodologies to select soil quality indicators is key to a successful soil quality evaluation (Dumanski and Pieri 2000; Ditzler and Tugel 2002).

The interactions of soil chemical, physical, and biological properties define an inherent soil quality and determine how effectively the soil performs ecosystem functions (Karlen *et al.* 1997). Biochemical and microbiological soil properties have been used as indicators of soil quality, both individually and combined, because of their sensitivity to environmental change compared with most physical and chemical properties (Chaer *et al*. 2009). However, the use of these parameters combined in a soil quality index (SQI) has not been widely studied. Romaniuk *et al*. (2011*b*) compared different methods of indicators selection to construct SQIs by considering diverse chemical, physical, biochemical and microbiological soil properties in an extensive production system. Those results showed that indices based only on biochemical and/or microbiological indicators had the same sensitivity as indices integrating physical, chemical and biological indicators to assess soil quality. However, the relative importance of indicators varied depending on land-use changes so that the indicators selected to assess soil quality in a given production system may not be useful in other production situations (Golchin and Asgari 2008).

In this study, the concept of 'soil quality' is focused on the preservation or improvement of selected soil properties. The objectives were (*i*) to evaluate the sensitivity of integrative SQIs constructed by considering diverse chemical, physical, and biological properties compared with biological SQIs integrated only by biochemical and microbiological indicators in assessing soil quality of an intensive horticultural production system; and (*ii*) to compare these results with those obtained for an extensive production system.

Materials and methods

Field site, treatments, and soil sampling

The study was conducted in an intensive horticultural production system (two crops per year) in La Plata, Buenos Aires province, Argentina. The soil was classified as Vertic Argiudoll (Soil Survey Staff 1999). Undisturbed reference soil (UN), conventional (C) and organic (O) plots with 5 years (O 5 and C 5) and >20 years (O 20 and C 20) of horticultural production were evaluated (Table 1). The plots were adjacent but spaced with a 5-m-wide boarder area. The size of each plot was 0.5 ha (50 m by 100 m). The main crops cultivated were lettuce, spinach, tomatoes, celery, zucchini, cabbage, beet, vetch, bean and fennel. Conventional and organic production plots were tilled with mouldboard plough. The 5-year production systems were uncultivated for 10 years before entering production. Input amendments in organic plots varied between 2 and 4 Mg ha^{-1} before planting the crop. The organic amendments were superficially applied and then incorporated to the first 20 cm soil depth by tillage operations. In conventional plots, the application rate of synthetic fertilisers varied between 50 and 150 kg ha^{-1}, and application doses of insecticides and fungicides ranged from 1 to 4 kg ha^{-1}.

The reference soil (UN) was adjacent to the horticultural plots, completely covered by vegetation, and had not been cultivated in the last 50 years. The predominant species were *Paspalum dilatatum*, *P. quadrifarium*, *Bromus unioloides*, *Cynodon dactylon*, *Stipa neesiana*, *Bothriochloa* sp., *Baccharis* sp.

Soil sampling was performed in September 2006 when all plots were uncultivated. Five single soil samples for each plot

Table 1. Description of fertilisers, fungicides, herbicides and insecticides applied in plots with 5 or 20 years of organic management (O 5, O 20), and 5 or 20 years of conventional management (C 5, C 20)

	O 5		C 5		O 20		C 20	
	Product	Doses	Product	Doses	Product	Doses	Product	Doses
Fertilisers	Animal manure	3-4 Mg ha^{-1}	Diamonic fosfate	100 kg ha^{-1}	Animal manure	3-4 Mg ha^{-1}	Diamonic fosfate	100 kg ha^{-1}
	Compost	2-3 Mg ha^{-1}	Urea	150 kg ha^{-1}	Compost	2-3 Mg ha^{-1}	Urea	150 kg ha^{-1}
	Bone meal	0,5-1 Mg ha^{-1}			Vegetable residues	1-2 Mg ha^{-1}		
Fungicides	–		Azoxystrobin (20%)	0,5-0,8 L ha^{-1}	–		Thiram (35%)	0,2 L 100 kg seed $^{-1}$
			Captan (50%)	2-3 kg ha^{-1}			Carbendazim (15%)	0,2 L 100 kg seed^{-1}
			Thiram (35%)	0,2 L 100 kg seed^{-1}				
Herbicides	Mechanical control		Glyphosate (48%)	2 L ha^{-1}	Mechanical control		Atrazine (50%)	2 L ha^{-1}
Insecticides	–		Endosulfan (35%)	1-2 L ha^{-1}	–		Chloropyrifos (48%)	0,9 L ha^{-1}
			Methidathion (40%)	0,2 L 100 kg seed^{-1}			Cypermethrin (25%)	0,1-0,15 L ha^{-1}

were randomly extracted with auger from 0 to 10 cm (soil depth 1) and from 10 to 20 cm (soil depth 2), in order to obtain pseudo-replicates, since each plot represents a field situation with different management history, and therefore it is impossible to obtain true replicates (Noellemeyer *et al*. 2008).

The five samples per plot required for biological analysis were stored at field moisture at 4°C. For chemical and physical analyses, soil samples were air-dried, sieved (<2 mm) and stored at room temperature.

Soil analyses

The physical analyses performed for soil depths 1 and 2 were bulk density (Blake 1965), particle size analysis (Bouyoucos 1927), structural stability (De Leenheer and De Boodt 1958) expressed as mean weight diameter (MWD) (Kemper and Rosenau 1986). Saturated hydraulic conductivity (K) was measured only (Klute 1965) in the 0–10 cm layer.

Soil chemical analysis included the determination of soil pH (1 : 2 soil/water), electrical conductivity of saturated soil paste, extractable phosphorus (P) (Bray and Kurtz 1945), total N (TN) using the Kjeldahl method proposed by Bremner and Mulvaney (1982), total organic carbon content (TOC) by the potassium dichromate method (Nelson and Sommers 1982), and total organic C stock (SC) calculated as described by Ellert and Bettany (1995).

Soil biological analysis involved biochemical and microbiological determinations. The biochemical analysis were particulate organic C (POC) (Cambardella and Elliott 1992), soil basal respiration (Resp) by titration after 7 days of soil samples incubation at 25°C (Jenkinson and Powlson 1976), soil microbial biomass C (MBC) determined by the chloroform fumigation–extraction method (Vance *et al*. 1987) using a conversion factor of 0.33, and soluble organic C (SOC) (Haynes 2005). The metabolic quotient (qCO_2) and the microbial coefficient (MBC/TOC) were obtained by calculation (Anderson and Domsh 1990).

The microbiological measurements were determined only for the 0–10 cm depth. Catabolic response profiles were measured according to Degens and Harris (1997) by short-term respiration responses (4 h at 25°C) of soil to the addition of 20 simple organic compounds (D-glucosamine, L-glutamine, L-arginine, L-glutamic acid, L-histidine, L-lysine, L-serine, D-glucose, D-mannose, L-ascorbic acid, citric acid, tartaric acid, gluconic acid, α-ketobutyric acid, α-ketoglutaric acid, DL-malic acid, malonic acid, pantothenic acid, quinic acid and uric acid). The catabolic evenness (E) was calculated using the Simpson–Yule index: $E = 1/\sum p^2{}_i$, where p_i is the respiration response to individual substrates as a proportion of total respiration activity induced by all substrates for a soil.

Phospholipid fatty acid methyl ester profiles (PLFA) were determined as reported by Schutter and Dick (2000) using a Hewlett-Packard 5890 series II (Agilent, Palo Alto, CA, USA) gas chromatography. The temperature program ramped from 150°C to 210°C at 5°C min^{-1} and held for 20 min. Peak identification was performed by comparison of retention times with known standards (bacterial acid methyl ester standard in methyl caproate, Cat. No. 47080-U; Sigma-Aldrich Co., St. Louis, MO, USA) and were reported as ratios of peak area to methyl hexadecanoate. Standard nomenclature was used to describe detected PLFAs. The sum of the i15 : 0, a15 : 0, 16 : 0, i16 : 0, 17 : 0, 20 : 0, 22 : 0 (saturated PLFAs) and 16 : 1w9, cy17 : 0, cy19 : 0, 18 : w9 (mono-unsaturated PLFAs) was used as a measure of bacterial biomass; and the PLFA 18:2w6 was used as a measure of fungal biomass for the calculation of the fungal/bacterial (F/B) ratio. For the total PLFA (TPLFA), the PLFAs 11 : 0, 12 : 0, 13 : 0, 14 : 0, saturated and mono-unsaturated PLFAs were considered. The indicators of stress conditions were the following ratios: saturated/mono-unsaturated (S/M), cyclopropil 17 : 0/precursors 16 : w9 (cy/pre), and the iso 15 : 0/anteiso 15 : 0 (i/a) PLFAs.

Steps for construction of soil quality indices

As one relevant criterion for a good soil quality indicator is easy and inexpensive measurement (Doran and Zeiss 2000), the soil measurements were classified as simple (chemical, physical, and biochemical variables) or complex (microbiological variables) depending on the cost, time and labour required for their determination. Separating the simple and complex measurements is a way of assessing the benefits of using one or another type of variable, by comparing their sensitivity.

Data were processed using the InfoStat statistics program (InfoStat 2007, National University of Córdoba, Argentina). The procedure used for the construction of the SQIs consisted in the following steps:

1. Analysis of variance (ANOVA) for selection of soil variables with statistically significant differences ($P < 0.05$) among soil situation, and with CV <40% (Wander and Bollero 1999).
2. Selection of a minimum dataset by principal component (PC) analysis considering all soil properties together (procedure A) or according to their classification in physical, chemical or biological (procedure B) (Fig. 1). Procedure B, unlike procedure A, ensures that at least one indicator of each type (physical, chemical and biological) is included in the SQI. For indicator selection, only the PCs with eigenvalues >1, and those that explained at least 10% of the variation in the data, were included. Within each PC, soil properties having absolute values within 10% of the highest factor loading were selected.
3. Linear normalisation of the indicators (Andrews *et al*. 2002*b*).
4. Integration of the final indicators by the weight additive method (Fig. 1) (Andrews *et al*. 2002*a*) to construct simple, complex and microbiological soil quality indices (SSQI, CSQI, MSQI).

The SSQI used physical, chemical and biochemical soil parameters, and the CSQI also included the microbiological variables. The MSQI only included biological variables (biochemical and microbiological soil properties).

The final values provided by the SQIs for each plot were statistically compared by ANOVA (at $P = 0.05$) and correlated with the varimax-rotated scores of PC 1 obtained by including soil parameters selected in the step 1.

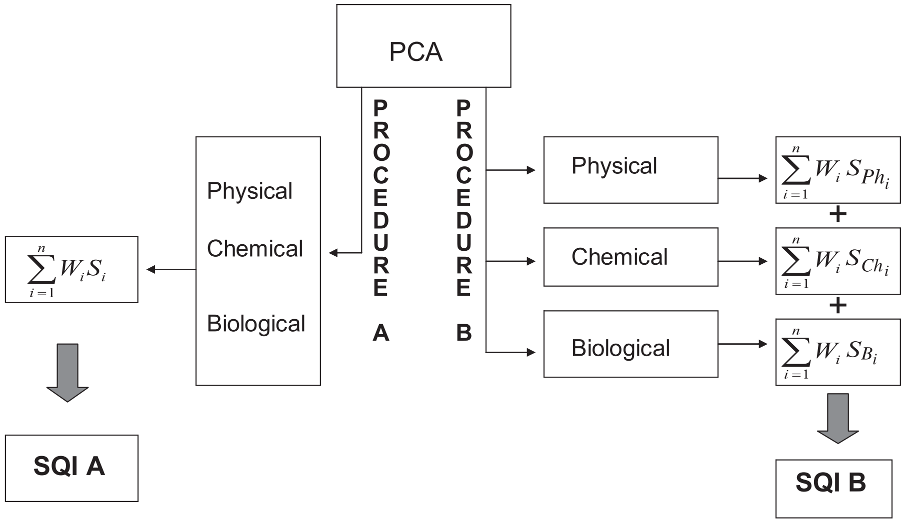

Fig. 1. Procedures applied in the construction of the soil quality indices (SQIs). PCA, Principal component analysis. Terms of the weight additive equation: *S*, the score of the indicator; *W*, the weighted factor derived from the PCA; Ph_i, physical indicators; Ch_i, chemical indicators; B_i, biological indicators.

More details of the procedures used in the selection of soil indicators and construction of the SQIs can be found in Romaniuk *et al.* (2011*b*).

Results

Construction of the soil quality indices

Table 2 shows the means soil physical, chemical and biological properties selected after the ANOVA in the studied plots. Most of the soil properties were selected for both soil depths (0–10 and 10–20 cm). The progressive homogenisation of the first 20 cm of soil caused by conventional tillage could explain the similar trends showed by most of the measured soil variables at 0–10 and 10–20 cm.

Table 3 presents the results of PC analysis of the soil properties. For soil physical measurements (Table 3, column III), the MWD 1 (0–10 cm depth) was selected. For the chemical parameters (Table 3, column IV), the TOC from the second soil layer (10–20 cm depth) and pH were retained according the selection criteria. However, pH as a soil quality indicator was not included because all values in the conventional management plots were within the optimum range for crop growth (Islam *et al.* 1980).

Among the biochemical properties (Table 3, column V), MBC of the first soil layer (MBC 1) and POC from the second soil layer (POC 2) were selected. When both biochemical and microbiological parameters were included in the PC analysis (Table 3, column IV), functional diversity (E), TPLFA, i/a (iso/anteiso) PLFA ratio, POC 2 and the soil respiration (Resp1) were retained.

When physical, chemical and biochemical properties were analysed (Table 3, column II), TOC and Resp 0–10 cm depth were retained. If all soil properties were included in the PC analysis (Table 3, column I), TOC 1, Resp 1 and the S/M ratio were selected.

Once normalised, indicators were weighted and integrated to obtain the SQIs shown in Table 4.

Evaluation and comparison of the soil quality indices

Figure 2 shows the values of SQIs. Results provided by the SQIs showed that, regardless of the applied management, all of the studied systems decreased quality compared with the reference soil (UN). The organic management system increased the quality of soils compared with the conventional management, independent of the number of years in production. Generally, the short-term organic management (O 5) had low impact on soil quality compared with UN, whereas equal time with conventional management (C 5) decreased soil quality significantly in all cases. Differences provided by the SQIs among management systems in the short term (O5 *v.* C5) were similar, but in the long term (O 20 *v.* C 20) were greater.

The SSQI A index differentiated the UN soil from those under cultivation (Fig. 2*a*) and discriminated according to management system between situations with the same time under horticulture. However, the index did not vary according to number of years under production. The index values were highly influenced by TOC from the first soil layer (0–10 cm depth). This soil property varied according time under production (5 *v.* 20 years production). Respiration measured in the first 10 cm depth contributed to the differentiation by management system (organic *v.* conventional).

The SSQI B (Fig. 2*b*) differentiated according to the number of years under production, and by the management system only for the plots with less time under horticulture (O5 *v.* C5), mainly influenced by the TOC from the second soil layer (10–20 cm depth). The MWD 1 contributed to showing variation between UN and the production plots, while the POC of the second soil layer (POC 2) increased differences according to the years in production. The MBC measured in the first 10 cm depth (MBC 1) was useful to differentiate time under production, and management system in the horticulture plots with 20 years of crop production.

The CSQI A (Fig. 2*c*) showed differences between management systems, but failed to differentiate according to

Table 2. Physical, chemical, and biological soil properties from soil depth 0–10 cm (named 1) and 10–20 cm (2) in the undisturbed plot (UN), and in plots with 5 or 20 years of organic management (O 5, O 20), and 5 or 20 years of conventionally management (C 5, C 20)

Values are mean ± s.d. BD, Bulk density; MWD, mean weight diameter; *K*, saturated hydraulic conductivity; TOC, total organic C; SC, stock C; TN, total N; P, extractable phosphorus; SOC, soluble organic C; POC, particulate organic C; MBC, microbial biomass C; Resp, basal soil respiration; qCO_2, metabolic quotient; MBC/C, microbial coefficient; E, functional evenness; TPLFA, total methyl ester phospholipid fatty acids; S/M, saturated/mono-unsaturated PLFA ratio; F/B, fungal/bacterial PLFA; i/a, iso/anteiso PLFA ratio; cy/pre, cyclopropil/precursors PLFA ratio. Within rows, means followed by the same letter are not significantly different at $P = 0.05$

	UN	O 5	C 5	O 20	C 20
BD 1 ($g\,cm^{-3}$)	1.07 ± 0.16a	1.23 ± 0.05b	1.25 ± 0.09b	1.26 ± 0.03b	1.36 ± 0.09b
MWD 1 (mm)	35 ± 20.45a	73 ± 15.79b	170 ± 19.53c	308 ± 35.05d	322 ± 36.00d
MWD 2 (mm)	156 ± 23.64a	220 ± 16.03b	245 ± 27.33b	305 ± 31.23c	335 ± 24.55c
K ($cm^3\,h^{-1}$)	9.39 ± 1.43b	9.30 ± 2.08b	9.29 ± 2.43b	3.34 ± 0.68a	2.36 ± 0.26a
TOC 1 ($g\,kg^{-1}$)	29.0 ± 4.4c	24.1 ± 1.3b	21.1 ± 2.1b	13.0 ± 0.9a	12.5 ± 2.3a
TOC 2 ($g\,kg^{-1}$)	26.3 ± 3.1c	24.8 ± 2.0c	20.9 ± 1.6b	13.0 ± 1.0a	13.8 ± 1.3a
SC 1 ($Mg\,ha^{-1}$)	30.44 ± 1.55c	29.59 ± 1.8c	22.70 ± 2.99b	16.37 ± 0.97a	17.61 ± 3.41a
SC 2 ($Mg\,ha^{-1}$)	36.11 ± 4.87c	34.36 ± 2.46c	29.33 ± 2.55b	18.33 ± 1.56a	19.48 ± 1.79a
pH 1	6.36 ± 0.16a	6.39 ± 0.20a	6.67 ± 0.14b	6.29 ± 0.04a	6.77 ± 0.16b
pH 2	6.36 ± 0.09a	6.37 ± 0.08a	6.69 ± 0.05b	6.23 ± 0.09a	6.70 ± 0.07b
TN 1 ($g\,kg^{-1}$)	2.8 ± 0.2d	2.5 ± 0.1c	2.2 ± 0.2c	1.3 ± 0.1a	1.7 ± 0.2b
TN 2 ($g\,kg^{-1}$)	2.4 ± 0.3c	2.3 ± 0.3c	2.2 ± 0.1c	1.2 ± 0.1a	1.7 ± 0.1b
P 1 ($mg\,kg^{-1}$)	27.05 ± 4.95a	14.09 ± 3.86a	112.4 ± 22.45c	48.64 ± 10.27b	156.8 ± 27.75d
P 2 ($mg\,kg^{-1}$)	19.06 ± 2.87a	18.45 ± 2.88a	121.5 ± 18.83c	36.16 ± 2.42b	151.2 ± 18.64d
SOC 1 ($\mu g\,g^{-1}$)	45.74 ± 5.31b	35.16 ± 6.17a	31.65 ± 6.66a	37.84 ± 4.90a	37.21 ± 4.31a
POC 1 ($g\,kg^{-1}$)	9.9 ± 2.7c	9.7 ± 1.6c	7.0 ± 1.3b	2.3 ± 0.6a	1.8 ± 0.8a
POC 2 ($g\,kg^{-1}$)	7.6 ± 1.8b	10.6 ± 1.7c	8.1 ± 1.4b	3.1 ± 0.7a	2.7 ± 0.7a
MBC 1 ($\mu g\,g^{-1}$)	337.4 ± 46.8d	151.7 ± 63.8c	80.2 ± 13.6b	109.9 ± 21.3b	28.5 ± 7.0a
Resp 1 ($\mu g\,g^{-1}\,h^{-1}$)	0.38 ± 0.04b	0.39 ± 0.20b	0.23 ± 0.03a	0.59 ± 0.09c	0.24 ± 0.04a
qCO_2 1 (μg C-CO_2 μg^{-1} MBC h^{-1}) × 10^{-3}	1.14 ± 0.14a	2.47 ± 0.33b	2.86 ± 0.41b	5.41 ± 0.50c	8.66 ± 1.51d
MBC/C 1 (%)	1.17 ± 0.16c	0.63 ± 0.26b	0.43 ± 0.09a	0.85 ± 0.22b	0.24 ± 0.12a
MBC/C 2 (%)	1.10 ± 0.29c	0.16 ± 0.06a	0.22 ± 0.09a	0.64 ± 0.16b	0.15 ± 0.02a
E	13.83 ± 0.50e	10.66 ± 0.06d	10.22 ± 0.06c	9.57 ± 0.39b	8.58 ± 0.22a
TPLFA	6.38 ± 0.77b	6.14 ± 0.47b	5.24 ± 0.67a	6.42 ± 0.62b	4.44 ± 0.49a
S/M	1.03 ± 0.06a	0.69 ± 0.06a	0.90 ± 0.13a	0.82 ± 0.02a	1.59 ± 0.41b
F/B	0.05 ± 0.01b	0.06 ± 0.01b	0.07 ± 0.01b	0.05 ± 0.01b	0.04 ± 0.01a
i/a	0.61 ± 0.12a	1.16 ± 0.07b	0.93 ± 0.33b	0.68 ± 0.18a	1.90 ± 0.18c
cy/pre	0.21 ± 0.05a	1.25 ± 0.31b	1.01 ± 0.40b	0.35 ± 0.11a	1.30 ± 0.35b

time under horticulture production. The TOC 1 and the Resp 1 showed the same trend as seen for SSQI A. The S/M ratio presented low influence in the index, increasing the final value of CSQI A for O 5, and decreasing the final value of the index for C 20. The sensitivity of this index to discriminate significantly among the study situations was lower than the sensitivity provided by the SSQI A and B. The incorporation of complex microbiological variables within an integrated SQI did not increase the sensitivity to differentiate between the studied situations.

The CSQI B (Fig. 2*d*) differentiated significantly ($P < 0.05$) for the period under horticulture, and for the management system applied. The introduction of the microbiological properties increased the sensitivity of the index compared with SSQI B, which considered only the biochemical properties. However, CSQI B was mainly influenced by the TOC 2, followed by the microbiological indicators, with less influence of the physical indicator (MWD 1).

The MSQI 1 (Fig. 2*e*) discriminated the same situations as CSQI A, showing differences for management system but not for production time. The MSQI 2 (Fig. 2*f*) presented a trend similar to MSQI 1, but with greater differences among the studied plots. The MSQI 2 significantly differentiated the UN from the production plots, and management system among situations with the same time under agricultural activity. The evenness (E) was the indicator with the highest incidence in MSQI 2, increasing the index value for UN and decreasing it for C 20. The Resp 1 and MBC 1 had a similar incidence, increasing the index value especially for UN and for the situation with organic management.

The ANOVA of PC 1 scores showed the same differences among plots ($P < 0.005$) as the CSQI B. Correlation coefficients of SQIs with varimax-rotated scores of PC 1 obtained from all significant data were 0.94 for SSQI A and CSQI A, 0.92 and 0.93 for SSQI B and CSQI B respectively, 0.88 for MSQI 1, and 0.76 for MSQI 2.

Discussion

According to results provided by SQIs, plots under horticultural production decreased soil quality compared with the reference situation, regardless of the management system applied. The

Table 3. Results of principal component analysis

BD, Bulk density; MWD, mean weight diameter; *K*, saturated hydraulic conductivity; TOC, total organic carbon; SC, stock C; TN, total N; P, extractable phosphorus; SOC, soluble organic carbon; POC, particulate organic C; MBC, microbial biomass C; Resp, basal soil respiration; qCO_2, metabolic quotient; MBC/TOC, microbial coefficient; E, functional evenness; TPLFA, total methyl ester phospholipid fatty acids; S/M, saturated/mono-unsaturated PLFA ratio; F/B, fungal/bacterial PLFA; i/a, iso/anteiso PLFA ratio; cy/pre, cyclopropil/precursors PLFA ratio

Soil properties considered	(I) Physical, chemical, biological			(II) Physical, chemical, biochemical		(III) Phys.	(IV) Chemical		Biological				
									(V) Biochem		(VI) Biochem., microbiological		
Principal component	1	2	3	1	2	1	1	2	1	2	1	2	3
Eigenvalues	17.29	6.78	2.79	14.42	5.47	3.6	6.86	3.04	4.61	2.46	8.12	3.48	1.84
Proportion	0.62	0.24	0.10	0.65	0.25	0.9	0.69	0.3	0.58	0.31	0.58	0.25	0.13
Weighted factor	0.65	0.25	0.10	0.72	0.28				0.65	0.35	0.6	0.26	0.14
Factor loadings													
BD 1	0.23	–0.06	–0.16	0.24	–0.11	0.47							
MWD 1	0.22	0.15	–0.05	0.25	0.12	0.51							
MWD 2	0.23	0.07	–0.09	0.26	0.03	0.53							
K	–0.2	–0.18	–0.10	–0.23	–0.17	–0.49							
TOC 1	–0.22	–0.13	0.09	–0.26	–0.09		0.37	0.13					
TOC 2	–0.21	–0.17	0.04	–0.25	–0.14		0.36	0.17					
SC 1	–0.22	–0.14	0.04	–0.25	–0.10		0.37	0.12					
SC 2	–0.21	–0.17	0.03	–0.25	–0.15		0.36	0.18					
pH 1	0.13	–0.29	0.15	0.11	–0.36		–0.16	0.52					
pH 2	0.16	–0.26	0.15	0.15	–0.32		–0.21	0.47					
TN 1	–0.20	–0.19	0.12	–0.24	–0.16		0.35	0.23					
TN 2	–0.16	–0.28	0.03	–0.20	–0.27		0.31	0.33					
P 1	0.20	–0.14	0.18	0.21	–0.20		–0.31	0.34					
P 2	0.19	–0.18	0.13	0.19	–0.25		–0.28	0.38					
SOC 1	–0.11	0.18	0.44	–0.12	0.23				0.34	–0.33	0.20	–0.35	–0.35
POC 1	–0.22	–0.16	–0.05	–0.25	–0.13				0.33	0.45	0.24	0.33	–0.25
POC 2	–0.18	–0.21	–0.21	–0.21	–0.20				0.22	0.55	0.17	0.45	–0.12
MBC 1	–0.22	0.08	0.23	–0.23	0.13				0.46	–0.01	0.32	–0.06	–0.29
Resp 1	–0.05	0.35	–0.19	0.03	0.40				0.18	–0.37	0.17	–0.26	0.49
qCO_2 1	0.23	0.05	0.09	0.25	0.02				–0.38	–0.33	–0.3	–0.26	0.08
MBC/TOC 1	–0.19	0.22	0.12	–0.19	0.28				0.44	–0.19	0.33	–0.18	–0.004
MBC/TOC 2	–0.14	0.24	0.28	–0.14	0.29				0.39	–0.32	0.28	–0.3	–0.10
E	–0.22	0.01	0.22								0.31	0.02	–0.33
TPLFA	–0.18	0.22	–0.16								0.31	–0.05	0.27
S/M	0.15	–0.07	0.44								–0.23	–0.25	–0.43
F/B	–0.16	–0.11	–0.30								0.21	0.39	0.15
i/a	0.17	–0.18	0.11								–0.31	0.02	–0.25
cy/pre	0.12	–0.28	–0.17								–0.27	0.31	–0.09

ecological equilibrium of soil can be perturbed easily by human intervention, resulting in a consistent decrease in its natural quality (Izquierdo *et al*. 2005). Crop management systems generally resulted in soil quality deterioration, leading to soil organic matter losses and structural degradation. Soil organic matter decline in many agroecosystems occurs because losses of C through oxidation and erosion by intensive cropping are not compensated by C inputs through the return of plant biomass (Ferreras *et al*. 2006), and sometimes not even by the inputs of organics amendments.

In agreement with the results found in the present study, several researchers (Shepherd *et al.* 2002; Pulleman *et al*. 2003; Liu *et al*. 2007) reported increases in soil quality under organic management compared with conventional management systems, by improvements in physical, chemical and, especially, in biological soil properties (Drinkwater *et al*. 1995; Monokrousos *et al*. 2006; Sparling *et al*. 2008) related with periodic inputs of organic amendments. This practice generally reduced the impact of tillage through favourable effects on soil structure provided by the organic inputs. However, there were no differences in the structural stability (MWD 1) and total organic matter contents (TOC 1 and 2) considering the long-term organic system (O 20) compared with the long-term conventional plot (C 20), so the impact of tillage was not compensated by the organic amendments in the long-term organic system. The inclusion of physical indicators is necessary to an overall understanding of changes in soil quality. Only the SQIs that included a physical indicator (MWD 1) were sensitive to differentiation by time under production (SSQI B and CSQI B).

Table 4. Soil properties, indexing procedures, and soil quality indices (SQIs) obtained

Procedures: A, all properties are considered together in the principal component analysis (PCA); B, groups of properties considered are separated in the PCA; Bch, biochemical soil properties; Mb, microbiological soil properties; TOC, total organic carbon; Resp, basal soil respiration; MWD, mean weight diameter; MBC, microbial biomass C; POC, particulate organic C; S/M, saturated/mono-unsaturated phospholipid methyl ester fatty acid (PLFA) ratio; E, functional evenness; TPLFA, total PLFA

Quality index	Properties	Procedure	SQI constructed
Simple soil quality index A (SSQI A)	Physical Chemical Biochemical	A	0.72 * TOC 1 + 0.28 * Resp 1
Simple soil quality index B (SSQI B)	Physical Chemical Biochemical	B	TOC 2 + MWD 1 + (0.65 * MBC 1 + 0.35 * POC 2)
Complex soil quality index A (CSQI A)	Physical Chemical Biological (Bch, Mb)	A	0.65 * POC 1 + 0.25 * Resp 1 + 0.10 * S/M
Complex soil quality index B (CSQI B)	Physical Chemical Biological (Bch, Mb)	B	TOC 2 + MWD 1+ (0.2 * (E + i/a + TPLFA) + 0,26 * POC 2 + 0.14 * Resp 1)
Microbiological soil quality index 1 (MSQI 1)	Biological (Bch, Mb)	B	0.2 * (E + i/a + TPLFA) + 0,26 * POC 2 + 0.14 * Resp 1
Microbiological soil quality index 2 (MSQI 2)	MBC Resp E	Expert variables selection	MBC 1+Resp 1+ E

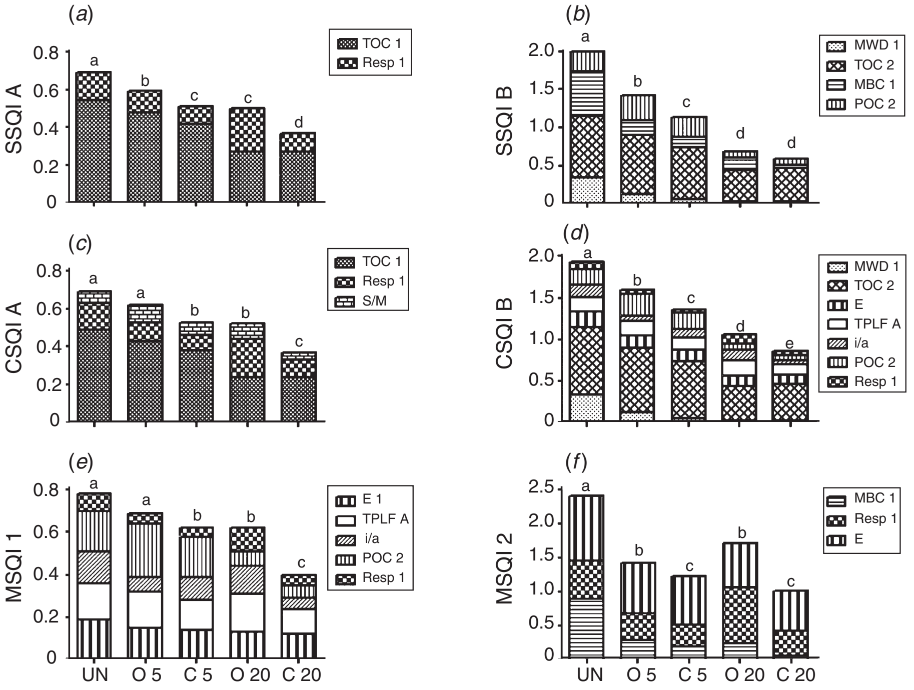

Fig. 2. Values of soil quality indices (SQIs) for plot treatments: undisturbed (UN), 5 years of organic management (O 5), 5 years of conventional management (C 5), 20 years of organic management (O 20) and 20 years conventional management (C 20). Within each part (*a*–*f*), bars with the same letter are not significantly different at $P = 0.05$. MWD, Mean weight diameter; TOC, total organic carbon; POC, particulate organic C; Resp, basal soil respiration; MBC, microbial biomass C; E, functional evenness; TPLFA, total phospholipid fatty acids; cy/pre, cyclopropil/precursors PLFA ratio; i/a, iso/anteiso PLFA ratio.

For the simple SQIs, the introduction of soil variables in groups in the PC analysis—so that the index comprised chemical, physical and biological indicators (procedure B)—did not increase the ability to discriminate between the studied situations. The SSQI A was more efficient in separating by management system, whereas SSQI B was able to differentiate according to number of years under production.

Andrews *et al*. (2002*a*) compared different methods of index construction in a horticultural system under organic, conventional and low-input management. However, only chemical variables were selected to represent the minimum dataset. The lack of biological indicators in the index could be a problem if the objective is to evaluate the soil quality of systems with organic amendments, which impacts directly on microbiological communities. An SQI must include all soil aspects to give a certain evaluation of the overall soil quality. The methodology proposed in this research, with the introduction of variables performed by groups according their classification into chemical, physical or biological properties, solved the problem generated by introducing all the variables together in the PC analysis.

In the CSQI A, the inclusion of microbiological variables in the SQI did not increase its sensitivity to differentiate among the studied situations compared with the SSQI A. The introduction of the microbiological variables in CSQI B increased the sensitivity of this index compared with SSQI B, which considered physical, chemical and biochemical variables. The TPLFA increased the index value for undisturbed and organic situations, whereas the i/a PLFA ratio stress indicator largely increased the index values for O 20 and decreased it for C 20. The functional diversity (E) did not increase the sensitivity of the index, although this indicator was the most sensitive in differentiation among situations when it was individually evaluated (Romaniuk *et al*. 2011*a*). This could be linked to the linear transformation of the indicators, as indicators with slight difference among situations (nevertheless statistically significant) provide similar values for the indicator in the index, and thus may hide its real sensitivity.

The MSQI 1 showed the same differences among situations as SSQI A. The lack of physical indicators in both indices composed only of biological properties (MSQI 1) or biological and chemical indicators (SSQI A) increased the final index values for the organic situations. It is known that biological soil properties are mainly affected by organic amendments, and this could hide the differences caused by the time under production with conventional tillage operations. Similar results were obtained with MSQI 2, in which the biological variables did not reflect the soil physical differences of the studied situations.

The same SQIs constructed in the present research were constructed for an extensive agriculture production system (Romaniuk *et al*. 2011*b*). By contrast, the results provided for the SQI in the extensive system showed that the MSQIs presented the same sensitivity as the integrated indices to differentiate the studied situations. Although many authors argue that changes in the microbial community can be used to predict the effects of organic and conventional management practices (Bending *et al*. 2000; Harris 2003; van Diepeningen *et al*. 2006), organic amendments could generate an exaggerated effect on the size and activity of the microbial community, masking physical differences between management systems, whereas in extensive production systems these microbial parameters are more discriminative.

For intensive horticultural production systems, the CSQI B, constructed by the introduction of variables in groups according to their classification into physical, chemical or biological, and considering microbiological variables, was the best to differentiate among situations differing by management system and years under production.

All of the SQIs constructed presented high correlation coefficients with the PC 1 varimax-rotated scores. The highest correlation values were for the indices integrated by physical, chemical and biological indicators. Microbiological indices, especially the MSQI 2, had thte lowest values, probably because those indices did not reflect the physical properties. The organic amendments could increase the biological activity and then mask other soil aspects such as physical soil quality.

Conclusions

The SQIs showed that plots under organic management systems present higher soil quality values than the conventional systems compared for the same number of years in production, but undisturbed plots had the highest SQIs. Only SQIs that included a physical indicator were able to differentiate by time under production. The SQI constructed by procedure B and considering microbiological complex measurements (CSQI B) was the most sensitive in discriminating situations with respect to time under horticulture, and management system. The microbiological SQIs presented the lowest sensitivity, as they did not reflect the physical properties of these situations. Organic amendments showed a great influence on the microbial community; therefore, microbiological indices could not provide reliable information on the soil quality in production systems with high inputs of organic materials.

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References

Anderson TH, Domsh KH (1990) Application of eco-physiological quotients (qCO_2 and qD) on microbial biomass from soils of different cropping histories. *Soil Biology & Biochemistry* **22**, 251–255. doi:10.1016/0038-0717(90)90094-G

Andrews SS, Karlen DL, Mitchell JP (2002*a*) A comparison of soil quality indexing methods for vegetable production systems in Northern California. *Agriculture, Ecosystems & Environment* **90**, 25–45. doi:10.1016/S0167-8809(01)00174-8

Andrews SS, Mitchell JP, Manicinelli R, Karlen DJ, Hartz TK, Horwath WR, Pettygrove GS, Scow KM, Munk DS (2002*b*) On-farm assessment of soil quality in California's Central Valley. *Agronomy Journal* **94**, 12–23. doi:10.2134/agronj2002.0012

Bending GD, Putland C, Rayns F (2000) Changes in microbial community metabolism and labile organic matter fractions as early indicators of the impact of management on soil biological quality. *Biology and Fertility of Soils* **31**, 78–84. doi:10.1007/s003740050627

Bindraban PS, Stoorvogel JJ, Jansen DM, Viaming J, Groot JJR (2000) Land quality indicators for sustainable land management: proposed method for yield gap and soil nutrient balance. *Agriculture, Ecosystems & Environment* **81**, 103–112. doi:10.1016/S0167-8809(00)00184-5

Blake GR (1965) Bulk density. In 'Methods of soil analysis. Part I. Physical and mineralogical properties, including statistics of measurement and sampling'. (Ed. CA Black) pp. 374–395. (American Society of Agronomy: Madison, WI, USA)

Bouyoucos GJ (1927) The hydrometer as a new method for the mechanical analysis of soils. *Soil Science* **23**, 343–354. doi:10.1097/00010694-192705000-00002

Bray RH, Kurtz LT (1945) Determination of total, organic and available forms of phosphorus in soils. *Soil Science* **59**, 39–46. doi:10.1097/00010694-194501000-00006

Bremner JM, Mulvaney CS (1982) Total nitrogen. In 'Methods of soil analysis. Part 2'. (Ed. AL Page) pp. 595–624. (American Society of Agronomy: Madison, WI, USA)

Cambardella CA, Elliott ET (1992) Particulate soil organic-matter across a grassland cultivation sequence. *Soil Science Society of America Journal* **56**, 777–783. doi:10.2136/sssaj1992.03615995005600030017x

Chaer GM, Myrold DD, Bottomley PJ (2009) A soil quality index based on the equilibrium between soil organic matter and biochemical properties of undisturbed coniferous forest soils of the Pacific Northwest. *Soil Biology & Biochemistry* **41**, 822–830. doi:10.1016/j.soilbio.2009.02.005

De Leenheer L, De Boodt M (1958) Determination of aggregate stability by the change in mean weight diameter. In 'Proceedings International Symposium of Soil Structure'. Gent. Vol. 24. pp. 290–300. (Med. Landbouw)

Degens BP, Harris JA (1997) Development of a physiological approach to measuring the catabolic diversity of soil microbial communities. *Soil Biology & Biochemistry* **29**, 1309–1320. doi:10.1016/S0038-0717(97)00076-X

Ditzler CA, Tugel AJ (2002) Soil quality field tools: experiences of USDA-NRCS Soil Quality Institute. *Agronomy Journal* **94**, 33–38. doi:10.2134/agronj2002.0033

Doran JW, Parkin TB (1994) Defining and assessing soil quality. In 'Defining soil quality for a sustainable environment'. (Eds JW Doran, DC Coleman, DE Bezdicek, BA Stewart) pp. 3–21. (Soil Science Society of America: Madison, WI, USA)

Doran JW, Zeiss MR (2000) Soil health and sustainability: managing the biotic component of soil quality. *Applied Soil Ecology* **15**, 3–11. doi:10.1016/S0929-1393(00)00067-6

Drinkwater LE, Letourneau DK, Workneh F, van Bruggen AHC, Shennan C (1995) Fundamental differences between conventional and organic tomato agroecosystems in California. *Ecological Applications* **5**, 1098–1112. doi:10.2307/2269357

Dumanski J, Pieri C (2000) Land quality indicators: research plan. *Agriculture, Ecosystems & Environment* **81**, 93–102. doi:10.1016/S0167-8809(00)00183-3

Ellert BH, Bettany JR (1995) Calculation of organic matter and nutrients stored in soils under contrasting management regimes. *Canadian Journal of Soil Science* **75**, 529–538. doi:10.4141/cjss95-075

Ferreras L, Gomez E, Toresani S, Firpo I, Rotondo R (2006) Effect of organic amendments on some physical, chemical and biological properties in a horticultural soil. *Bioresource Technology* **97**, 635–640. doi:10.1016/j.biortech.2005.03.018

Ge T, Nie S, Wu J, Shen J, Xiao H, Tong CH, Huang D, Hong Y, Iwasaki K (2011) Chemical properties, microbial biomass, and activity differ between soils of organic and conventional horticultural systems under greenhouse and open field management: a case study. *Journal of Soils and Sediments* **11**, 25–36. doi:10.1007/s11368-010-0293-4

Golchin A, Asgari H (2008) Land use effect on soil quality indicators in north-eastern Iran. *Australian Journal of Soil Research* **46**, 27–36. doi:10.1071/SR07049

González M, Gomez E, Comese R, Quesada M, Conti M (2010) Influence of organic amendments on soil quality potential indicators in an urban horticultural system. *Bioresource Technology* **101**, 8897–8901. doi:10.1016/j.biortech.2010.06.095

Govaerts B, Sayre KD, Deckers J (2006) A minimum data set for soil quality assessment of wheat and maize cropping in the highland of Mexico. *Soil & Tillage Research* **87**, 163–174.

Harris JA (2003) Measurements of the soil microbial community for estimating the success of restoration. *European Journal of Soil Science* **54**, 801–808. doi:10.1046/j.1351-0754.2003.0559.x

Haynes RJ (2005) Labile organic matter fractions as a central component of the quality of agricultural soils: an overview. *Advances in Agronomy* **85**, 221–268. doi:10.1016/S0065-2113(04)85005-3

Herrick JE, Brown JR, Tugel AJ, Shaver PL, Havstad KM (2002) Application of soil quality to monitoring and management: Paradigms from rangeland ecology. *Agronomy Journal* **94**, 3–11.

InfoStat (2007) 'InfoStat, versión 1.1. Manual del usuario.' Primera Edición. Grupo InfoStat, FCA, Universidad Nacional de Córdoba. (Editorial Brujas: Córdoba, Argentina)

Islam AKMS, Edwards DG, Asher CJ (1980) pH optima for crop growth results of a flowing solution culture experiment with six species. *Plant and Soil* **54**, 339–357. doi:10.1007/BF02181830

Izquierdo I, Caravaca F, Alguacil MM, Hernandez G, Roldán A (2005) Use of microbiological indicators for evaluating success in soil restoration after revegetation of a mining area under subtropical conditions. *Applied Soil Ecology* **30**, 3–10. doi:10.1016/j.apsoil.2005.02.004

Jenkinson DS, Powlson DS (1976) The effects of biocide treatments on metabolism in soil. A method for measuring soil biomass. *Soil Biology & Biochemistry* **8**, 209–213. doi:10.1016/0038-0717(76)90005-5

Karlen DL, Mausback MJ, Doran JW, Cline RG, Harris RF, Schuman GE (1997) Soil quality: a concept, definition and framework for evaluation. *Soil Science Society of America Journal* **61**, 4–10. doi:10.2136/sssaj1997.03615995006100010001x

Karlen DL, Gardner JC, Rosek MJ (1998) A soil quality framework for evaluating the impact of CRP. *Journal of Production Agriculture* **11**, 56–60.

Kemper WD, Rosenau RC (1986) Aggregate stability and size distribution. In 'Methods of soil analysis. Part 1'. 2nd edn (Ed. A Klute) pp. 425–442. (ASA, SSSA: Madison, WI, USA)

Klute A (1965) Laboratory measurement of hydraulic conductivity of saturated soil. In 'Methods of soil analysis. Part I. Physical and mineralogical proprieties, including statistics of measurement and sampling'. (Ed. CA Black) pp. 210–221. (ASA: Madison, WI, USA)

Larson WE, Pierce FJ (1994) The dynamic of soil quality as a measure of sustainable management. In 'Defining soil quality for a sustainable environment'. SSSA Special Publication No. 35. (Eds JW Doran, DC Coleman, DE Bezdicek, BA Stewart). pp. 53–72. (Soil Science Society of America: Madison, WI, USA)

Liu B, Tu C, Hu S, Gumpeterz M, Beagle Ristaino J (2007) Effect of organic, sustainable and conventional management strategies in grower fields on physical, chemical, and biological factors and the incidence of southern blight. *Applied Soil Ecology* **37**, 202–214. doi:10.1016/j.apsoil.2007.06.007

McCool DK, Pannkuk CD, Kennedy AC, Fletcher PS (2008) Effects of burn/low-till on erosion and soil quality. *Soil & Tillage Research* **101**, 2–9. doi:10.1016/j.still.2008.05.007

McGrath D, Zhang CS (2003) Spatial distribution of soil organic carbon concentrations in grassland of Ireland. *Applied Geochemistry* **18**, 1629–1639. doi:10.1016/S0883-2927(03)00045-3

Melero S, Porras JCR, Herencia JF, Madejon E (2006) Chemical and biochemical properties in a silty loam soil under conventional and organic management. *Soil & Tillage Research* **90**, 162–170. doi:10.1016/j.still.2005.08.016

Monokrousos N, Papatheodoru EM, Diamantopoulus JD, Stamou GP (2006) Soil quality variables in organically and conventionally cultivated field sites. 2006. *Soil Biology & Biochemistry* **38**, 1282–1289. doi:10.1016/j.soilbio.2005.09.023

Nelson DW, Sommers E (1982) Total carbon, organic carbon, and organic matter. In 'Methods of soil analysis. Part 2'. 2nd edn Agronomy Monograph No. 9. (Ed. AL Page) pp. 539–579. (ASA: Madison, WI, USA)

Noellemeyer E, Frank F, Alvarez C, Morazzo G, Quiroga A (2008) Carbon contents and aggregation related to soil physical and biological properties under a land-use sequence in the semiarid region of central Argentina. *Soil & Tillage Research* **99**, 179–190. doi:10.1016/j.still.2008.02.003

Pulleman M, Jongmans A, Marinissen J, Bouma J (2003) Effects of organic versus conventional arable farming on soil structure and organic matter dynamics in a marine loam in the Netherlands. *Soil Use and Management* **19**, 157–165. doi:10.1079/SUM2003186

Raiesi F (2006) Carbon and N mineralization as affected by soil cultivation and crop residue in a calcareous wetland ecosystem in Central Iran. *Agriculture, Ecosystem & Environment* **112**, 13–20.

Romaniuk R, Giuffré L, Costantini A, Nannipieri P (2011*a*) Assessment of soil microbial diversity measurements as indicators of soil functioning in organic and conventional horticulture systems. *Ecological Indicators* **11**, 1345–1353. doi:10.1016/j.ecolind.2011.02.008

Romaniuk R, Giuffré L, Costantini A, Bartoloni N, Nannipieri P (2011*b*) A comparison of indexing methods to evaluate soil quality: the role of soil microbiological properties. *Soil Research* **49**, 733–741. doi:10.1071/SR11147

Schutter ME, Dick RP (2000) Comparison of fatty acid methyl ester (FAME) methods for characterizing microbial communities. *Soil Science Society of America Journal* **64**, 1659–1668. doi:10.2136/sssaj2000.6451659x

Shepherd MA, Harrison R, Webb J (2002) Managing soil organic matter implications for soil structure on organic farms. *Soil Use and Management* **18**, 284–292. doi:10.1079/SUM2002134

Soil Survey Staff (1999) 'Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys.' 2nd edn. USDA Handbook 436. (Natural Resources Conservation Service, U.S. Department of Agriculture)

Sparling G, Schipper LA, Yeates GW, Aislabie J, Vojvodic-Vukovic M, Ryburn J, Di HJ, Hewitt AE (2008) Soil characteristics, belowground diversity and rates of simazine mineralization of a New Zeland Gley Soil in a chronosequence under horticultural use. *Biology and Fertility of Soils* **44**, 633–640. doi:10.1007/s00374-007-0247-1

van Diepeningen AD, de Vos OJ, Korthals GW, Van Bruggen AHC (2006) Effects of organic versus conventional management on chemical and biological parameters on agricultural soils. *Applied Soil Ecology* **31**, 120–135. doi:10.1016/j.apsoil.2005.03.003

Vance ED, Brookes PC, Jenkinson DS (1987) An extraction method for measuring soil microbial biomass C. *Soil Biology & Biochemistry* **19**, 703–707. doi:10.1016/0038-0717(87)90052-6

Wander MM, Bollero GA (1999) Soil quality assessment of tillage impacts in Illinois. *Soil Science Society of America Journal* **63**, 961–971. doi:10.2136/sssaj1999.634961x

Zhang B, Zhang Y, Chen D, White RE, Li Y (2004) A quantitative evaluation system of soil productivity for intensive agriculture in China. *Geoderma* **123**, 319–331.