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Application of soil quality indices to assess the status of agricultural soils irrigated with treated wastewaters

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Abstract. The supply of water is limited in some parts of the Mediterranean region, such as southeastern Spain. The use of treated wastewater for the irrigation of agricultural soils is an alternative to using better-quality water, especially in semi-arid regions. On the other hand, this practice can modify some soil properties, change their relationships and influence soil quality. In this work two soil quality indices were used to evaluate the effects of irrigation with treated wastewater in soils. The indices were developed studying different soil properties in undisturbed soils in SE Spain, and the relationships between soil parameters were established using multiple linear regressions. These indices represent the balance reached among properties in "steady state" soils. This study was carried out in four study sites from SE Spain irrigated with wastewater, including four study sites. The results showed slight changes in some soil properties as a consequence of irrigation with wastewater, the obtained levels not being dangerous for agricultural soils, and in some cases they could be considered as positive from an agronomical point of view. In one of the study sites, and as a consequence of the low quality wastewater used, a relevant increase in soil organic matter content was observed, as well as modifications in most of the soil properties. The application of soil quality indices indicated that all the soils of study sites are in a state of disequilibrium regarding the relationships between properties independent of the type of water used. However, there were no relevant differences in the soil quality indices between soils irrigated with wastewater with respect to their control sites for all except one of the sites, which corresponds to the site where low quality wastewater was used.

1 Introduction

In the southeastern region of Spain, the accessibility to groundwater is low due to the climate, rapid development of agricultural and tourist activities and fast expansion of the industrial sector which have produced an over-exploitation of aquifers. For this reason, freshwater availability is a current limiting factor in Mediterranean areas, and it is necessary to find alternatives to satisfy the strong water demand. Consequently, any activities taken to combat water scarcity challenges should be sustainable and should not reduce the natural resources or damage the environment.

The application of wastewater to irrigate agricultural soils is not a new practice (Day et al., 1974; Weber et al., 1996; Brar et al., 2002; Mohammad and Mazahreh, 2003; Pedrero et al., 2010). The reuse of industrial and urban wastewater has increased in many places principally because of demand by the agriculture sector. One of the best options for using treated wastewater can be the irrigation of agricultural soils, which allows the retention of a large amount of fresh water for other purposes (Pescod et al., 1992). Although the idea is currently receiving greater consideration because of the global water crisis, this reuse has been practiced all over the world (Asano, 1991; Keremane and Mckay, 2008). Substitution of freshwater by treated wastewater, richer in nutrients, is a key conservation strategy contributing to agricultural production (Rattan et al., 2005; Lin et al., 2006; Mekki et al., 2006; Rosabal et al., 2007).

Another environmental problem in the Mediterranean area is soil degradation. In some cases this degradation is due to the kind of agricultural irrigation applied, in many cases, using low-quality waters (waters with a very low degree of depuration and consequently with high salt content and in some cases contaminant compounds). Additionally, under semi-arid conditions, where the precipitation is less than the potential evaporation, the soils are prone to organic matter loss (Anderson, 2003), because under these climate conditions the high temperatures produces a fast organic matter oxidation, and due to the scarcity of rainfall, the vegetation cover is very low and, therefore, there are low inputs of organic matter into the soil. The alternative use of treated wastewater, could offer an additional source of organic matter and nutrients, the recovery of soil properties and increasing the storage of organic carbon in the soil in the medium-term (Burns et al., 1985; Friedel et al., 2000).

However, these practices may have adverse effects on soil quality. Agricultural management has been considered as one of the greatest causes of soil degradation (Kieft, 1994). Continuous soil tillage and the incorporation of organic residues or fertilisation could provoke alteration in some soil properties: organic matter, aggregate stability and enzyme activity (Caravaca et al., 2002; Gardi et al., 2002). Any disturbance in soil properties is usually accompanied by a loss of soil quality (Zornoza et al., 2007a). The evaluation of soil quality could be helpful to assess the level of disturbance in agricultural soils and useful in deciding the best alternative to having an adequate crop production preserving the soil quality (Karlen et al., 1997).

In the last years, there has been a growing trend in publications based on the use of biological and biochemical properties in evaluating soil quality due to the high sensibility of these properties (Trasar-Cepeda et al., 1998; Caldwell et al., 1999; Badiane et al., 2001; Filip, 2002; Salamanca et al., 2002; Wick et al., 2002; Ruf et al., 2003; Bastida et al., 2008) and based on an integration of physical, chemical and biological properties, owing to the close interaction among these properties in soil (Wander and Bollero, 1999; Andrews and Carroll, 2001; Aon et al., 2001; Chapman et al., 2003; Sparling et al., 2004).

Multiple linear regressions have also been successfully used as a method to choose the indicators to form part of the quality index and also as a tool to create algorithms to evaluate soil quality (Trasar-Cepeda et al., 1998; Emmerling and Udelhoven, 2002; Lentzsch et al., 2005). With this methodology, a variable is calculated by linear combination of others. Furthermore, only the variables that significantly explain the highest variance in the predicted variable are chosen. Thus, this method is also useful in reducing the number of soil indicators forming part of the index (Caravaca et al., 2002).

Although, there are not previous studies using soil quality indices to assess the use of wastewater for irrigation in agriculture, there are some that used soil quality indices to evaluate the effect of soil contamination with industrial and municipal wastes, organic fertilisation or irrigation with poor quality water under different crops (Puglisi et al., 2005). We used two indices, developed by Zornoza et al. (2007a), to evaluate the effects of medium and long-term irrigation with treated wastewater on the soil quality of some agricultural soils of SE Spain.

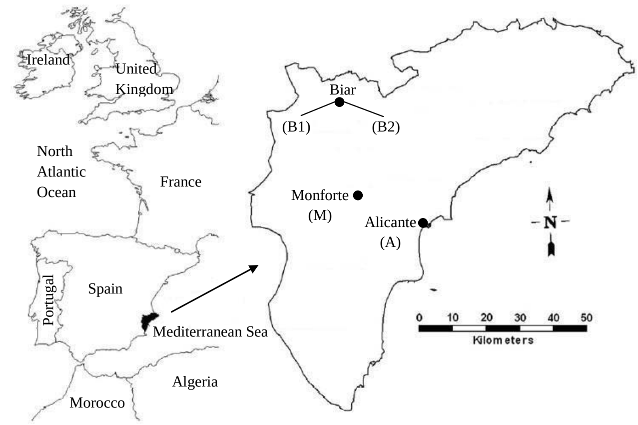

Fig. 1. Location of the study sites.

2 Materials and methods

2.1 Study sites and soil sampling

Three areas in the province of Alicante were selected for the study (Fig. 1), called Alicante (A), Monforte del Cid (M) and Biar (B), according to their geographical location. In the Biar area, two sites were sampled (B1 and B2). In all the four sites wastewater was used for irrigation.

In Table 1 the main characteristics of study sites are shown. Site A is agricultural land near to Alicante city dedicated to oranges. In this site there are two plots, one that has been irrigated with treated wastewater for 40 years (AR), and the other that has been irrigated with fresh water during the same period (AC). Site M is orchard land with a grape crop irrigated with treated wastewater for 20 years (MR) and its control site was irrigated with fresh water for the same period of time (MC). In both areas irrigation has been carried out by drip. Site B1 is agricultural land with a grape crop irrigated using treated wastewater for two years (B1R) and control irrigated with fresh water (B1C), in this case the irrigation method used was flooding. Site B2 is land near to a wastewater treatment plant, where there are two plots, one that has been irrigated with very low quality wastewater for a long term (20 years) (B2R) and control plot (B2C) close to this is an area dedicated to almond crop with similar soil conditions and not irrigated with wastewater.

B2R is a 2 ha plot that has been used as a "green filter" for approximately 20 years and was irrigated with "low quality" wastewaters, which had a very low degree of depuration. Analytical data from 1994 to 2000 indicates very high levels of organic load in the wastewater (In Table 2 the mean values from monthly analytical data are shown. Source: EPSAR, 2010).

Table 1. Study sites, irrigation methods, climatic parameters and soil characteristics.

Site[a]	Water type used[b]	Period of irrigation (years)	Irrigation method	Tm[c] (°C)	Pm[c] (mm)	Soil Type (SSS, 2010)	Texture[d] (% sand, silt clay)	OM[e] (%)	pH	$CaCO_3$ (%)
AC	FW	40	Drip	17.9	301	Xerorthent	Silty loam (2,56,42)	3.8	8.3	53
AR	WW	40	Drip			Xerorthent	Silty clay loam (7,77,16)	5.0	7.9	54
MC	FW	20	Drip	18.3	335	Xerorthent	Clay loam (56,22,22)	3.2	8.3	46
MR	WW	20	Drip			Xerorthent	Clay loam (56,20,24)	4.5	8.1	48
B1C	FW	2	Flooding	14.5	486	Xerofluvent	Silty clay loam (30,45,25)	2.0	8.6	42
B1R	WW	2	Flooding				Clay loam (26,45,29)	2.0	8.9	43
B2C	–	–	–	14.5	486	Xerofluvent	Sandy clay loam (74,8,18)	1.0	8.7	25
B2R	WW	20	Flooding				Sandy clay loam (60,18,22)	8.0	7.5	34

[a] A: Alicante; M: Monforte; B: Biar; C: Control plots without use of wastewater; R: plots with wastewater irrigation [b] FW: fresh water; WW: wastewater [c] Mean annual temperature (Tm) and mean annual precipitation (Pm). [d] Sand: 2–0.02 mm; silt: 0.02–0.002 mm; clay: <0.002 mm. [e] OM: organic matter.

Table 2. Mean values of main properties of irrigation wastewaters used in the study.

Parameter	B1R	B2R	AR	MR
EC ($\mu S\,cm^{-1}$)	1915	4000	3088	1856
BOD5 ($mg\,O_2\,l^{-1}$)	13.5	337	13	19
COD ($mg\,O_2\,l^{-1}$)	59.6	819	52	74
SS ($mg\,l^{-1}$)	18.5	207	22	19

EC: Electrical conductivity; BOD_5: biological oxygen demand; COD: Chemical Oxygen Demand; SS: suspended solids.

Soil samplings were carried out in June 2010. Six samples per study site were taken from the 0–5 cm depth ($n = 48$). The samples were air-dried in the laboratory at room temperature (∼ 25 °C) for a week. After that, they were sieved to 2 mm for analyses, except for aggregate stability soil samples aliquots were sieved between 4–0.25. For all analyses, two replicates per sample were used to reduce the analytical error.

2.2 Soil quality indices

Zornoza et al. (2007b) established two models for soil quality evaluation. Both models were developed using multiple linear regressions between physical, chemical and biochemical properties in undisturbed forest soils in SE Spain, representing the relationship between soil parameters at "steady state". The models were latter validated using undisturbed and disturbed soils subjected to perturbations such as the use of land for agriculture (Zornoza et al., 2008). Model 1, that explained 92 % of the variance in soil organic carbon (SOC) showed that the SOC can be calculated by the linear combination of 6 physical, chemical and biochemical properties (acid phosphatase, water holding capacity (WHC), electrical conductivity (EC), available phosphorus, cation exchange capacity (CEC) and aggregate stability (AS)). Model 2 explained 89 % of the SOC variance, which can be calculated by means of 7 chemical and biochemical properties (urease, phosphatase, and ß-glucosidase activities, pH, EC, P and CEC). We use the residual (difference between calculated SOC by models and real SOC measured in laboratory) as soil quality indices. The soil will be equilibrated if residuals are near 0 or inside confidence intervals of the models (95 %).

Model 2 is more sensitive owing to the high sensitivity of biochemical indicators (enzyme activities) (Nannipieri et al., 1990; Dick et al., 1996; Van Brugger and Semenov, 2000). Model 1 is less sensitive than Model 2, but suitable for assessing severe states of degradation due to physical and chemical properties (Filip, 2002; Reynolds et al., 2002).

Climatic factors have a strong influence on soil, for this reason, the models also include the mean annual precipitation (Pm) of each study site as an independent variable in the regressions, divided in two categories (Pm < 350 mm and Pm > 350 mm). The selection of category was in function of Pm for each area (Table 1). Therefore, there are two equations for both models, exposed below; the first formula (A and C) corresponds to multiple linear regression for soils with Pm < 350 mm, in our case, Alicante and Monforte sites. The second formula (B and D), adds a correction over the previous formula for soils placed in sites with Pm > 350 mm, in this study both the sites located in Biar. In these equations: SOC is expressed in $g\,kg^{-1}$, phosphatase and ß-glucosidase activities in μmol *p*-nitrofenol $g^{-1}\,h^{-1}$, urease activity in μmol $NH4^{+}\,g^{-1}\,h^{-1}$, WHC and AS in %, available phosphorus in $mg\,kg^{-1}$, EC in $\mu S\,cm^{-1}$ and CEC in $cmol^{+}\,kg^{-1}$.

In Model 1, SOC (transformed to Ln to achieve normality) can be calculated by the following equations:

$$\mathrm{Ln}\ (\mathrm{SOC}) = \mathrm{A}\ (\text{for Pm} < 350\text{mm});$$

$$\text{or Ln}\ (\mathrm{SOC}) = \mathrm{A} + \mathrm{B}\ (\text{for Pm} < 350\text{mm})$$

$$\mathrm{A} = 2.459 + 0.090\ (\text{phosphatase}) + 0.010\ (\mathrm{WHC})$$

$$+ 0.001\ (\mathrm{EC}) - 0.009\ (\text{available phosphorus})$$

$$+ 0.012\ (\mathrm{CEC}) + 0.001\ (\mathrm{AS})$$

$B = -0.138 - 0.007\ (WHC) + 0.059\ (P) + 0.008\ (AS)$

This model explains 92 % of the variance in SOC. The confidence interval (CI) at 95 % of the residuals distribution of the model ranged from –0.21 to 0.21.

With Model 2, SOC (transformed to Ln) can be calculated by following equations:

$\mathrm{Ln}\ (SOC) = C$ (for Pm < 350 mm); or $\mathrm{Ln}\ (SOC)$

$= C + D$ (for Pm < 350 mm) $C = 5.527$

$+\ 0.150$ (phosphatase) $-\ 0.064$ (Urease)

$-\ 0.088\ (\beta -$ glucosidase$) - 0.291\ (pH) + 0.001$

$(EC) + 0.028$ (available phosphorus) $+ 0.028\ (CEC)$

$D = 0.037 + 0.208\ (\beta -$ glucosidase$) - 0.015\ (CEC)$

This model explains 89 % of the variance in SOC. The confidence interval (CI) (at 95 %) ranged from –0.23 to 0.23 (Zornoza et al., 2008).

Any disturbance in soil must be accompanied by the modification of its properties and its equilibrium as observed in undisturbed forest soils. As a consequence, SOC calculated by the models (SOCc) is no longer an accurate estimation of the actual SOC determined in laboratory (SOCa). For a non-disturbed soil, in which these properties are balanced with organic matter, the values of residuals are 0 (SOCc = SOCa). Accordingly, as disturbing practices provoke a disruption of this equilibrium, SOCc should be lower or higher than the actual SOC, and degraded soils should generate residuals with values < or > 0. In addition, the more the degree of degradation increases, the more the values of SOCc should differ from the values of SOCa. For this reason, a soil quality index (SQI) was obtained by calculation of the model residuals:

SQI = model residual = SOCc – SOCa

SQI 1 = model 1 residual = SOCc – SOCa

SQI 2 = model 2 residual = SOCc – SOCa

These two models of SQI have been applied to the different sites of this study. We hypothesised that soils with more sustainable management practices should result in SQI ≈ 0 (within the 95 % CI of the residuals distribution of the models). On the contrary, in soils with damaging tillage practices or recent changes in management, SQI should be < or > 0.

2.3 Analytical methods

Soil pH was analysed in a 1:2.5 w/v, electrical conductivity (EC) in a 1:5 w/v, texture determined by the Bouyoucos method (Gee and Bauder, 1986). Soil organic carbon (SOC) was determined by Walkley and Black (1934). Available phosphorus was determined by the Burriel-Hernando method (Díez, 1982). Water holding capacity (WHC) was assayed by the method exposed by Forster (1995). Aggregate stability (AS) was measured using the method of Roldán et al. (1994); this method examines the proportion of aggregates that remain stable after a soil sample (sieved between 4–0.25 mm) is subjected to an artificial rainfall of known energy (270 J m^{-2}). Cation exchange capacity (CEC) was measured by the method described by Roig et al. (1980). Urease activity was measured according to the method of Nannipieri et al. (1980). Acid phosphatase activity was assayed by the method of Tabatabai and Bremmer (1969). The activity of ß-glucosidase was determined according to Tabatabai (1982).

2.4 Statistical analysis

The fitting of the data to a normal distribution for all properties measure was checked with the Kolmogorov-Smirnov test at $P<0.05$. To compare the effect of irrigation between the different types of waters, a T-Student test was developed at $P<0.05$. All statistical analysis was performed with the SPSS programme (Statistical Programme for the Social Sciences 18.0).

3 Results

3.1 Soil properties

Table 3 shows the soil physical, chemical and biochemical properties analysed for every study site. The results show that there are some statistical differences although not very significant in absolute values between soils irrigated with treated wastewater and soils irrigated with fresh water from studied areas of Alicante, Monforte and Biar 1. However, large differences were found in soils from Biar 2 due to the irrigation with wastewater. In the Alicante site, soils irrigated with wastewater showed significant highest contents of soil carbon, phosphatase activity and available phosphorous. In addition, a significant decrease in pH was observed in this area compared with its control site. There were no statistical differences for the rest of the parameters. In the Monforte site there were statistical differences between the types of irrigation applied, with mean values moderately higher for SOC, and CEC, in the soils irrigated with treated wastewater. In the Biar 1 site only a moderate increase of EC was observed in soils irrigated with treated wastewater with respect to the soils irrigated with fresh water. A slight increase in available phosphorus was also detected. The rest of the parameters suffered almost no variation due to the type of water used for irrigation.

All the parameters analysed showed statistical differences because of the use of wastewater, except for WHC. In this case irrigation with wastewater of lower quality has produced relevant changes in almost all soil properties. Soil organic carbon content has increased from 3 to 88 g kg^{-1}. EC has increased more than twice from its initial values. The same behaviour was observed for the percentage of stable aggregates,

Table 3. Mean values ± standard deviation and t-student values of the soil properties for each site.

Site[a]	SOC	pH	EC	CEC	phosphorus	WHC	AS	Phosphatase	Urease	B−glucosidase
	$g\,kg^{-1}$		$\mu S\,cm^{-1}$	$cmol^{+}\,kg^{-1}$	$mg\,kg^{-1}$	%	%	$\mu mol\,PNP\,g^{-1}\,h^{-1}$	$\mu mol\,NH_4^{+}\,g^{-1}\,h^{-1}$	$\mu mol\,PNP\,g^{-1}\,h^{-1}$
AC	22 ± 4	8.3 ± 0.1	412 ± 28	10.2 ± 0.9	163.4 ± 29.3	52 ± 3	40 ± 16	1.52 ± 0.46	7.54 ± 1.63	1.96 ± 0.41
AR	30 ± 2	7.9 ± 0.1	496 ± 83	9.8 ± 1.0	213.8 ± 27.4	52 ± 3	58 ± 16	2.29 ± 0.37	9.29 ± 1.78	2.18 ± 0.19
t	–4.5***	6.8***	–2.4*	n.s.	–3.1*	n.s.	n.s.	–3.3*	n.s.	n.s.
MC	19 ± 4	8.3 ± 0.1	339 ± 61	6.1 ± 0.6	109.8 ± 19.8	50 ± 2	45 ± 5	1.20 ± 0.32	4.83 ± 0.97	1.58 ± 0.46
MR	26 ± 2	8.1 ± 0.1	478 ± 97	7.6 ± 1.6	133.4 ± 9.9	55 ± 8	39 ± 10	1.92 ± 0.81	4.89 ± 1.02	1.12 ± 0.44
t	9.7***	–3.1*	n.s.	7.6***	11.5***	4.9**	7.7***	8.3***	11.3***	7.7**
B1C	12 ± 1	8.6 ± 0.1	186 ± 24	5.5 ± 0.3	14.2 ± 1.5	50 ± 3	49 ± 5	0.60 ± 0.09	1.60 ± 0.44	0.49 ± 0.08
B1R	12 ± 1	8.9 ± 0.1	359 ± 33	5.9 ± 0.8	19.7 ± 3.9	49 ± 6	42 ± 8	0.63 ± 0.09	1.50 ± 0.35	0.54 ± 0.13
t	n.s.	7.1***	10.4***	n.s.	3.2*	n.s.	n.s.	n.s.	n.s.	n.s.
B2C	3 ± 1	8.9 ± 0.1	76 ± 9	1.0 ± 0.2	19.3 ± 1.9	27 ± 2	36 ± 13	0.28 ± 0.08	5.93 ± 3.79	0.41 ± 0.16
B2R	88 ± 16	7.8 ± 0.1	160 ± 20	18.0 ± 3.7	234.9 ± 34.0	25 ± 7	85 ± 1	3.31 ± 0.81	34.83 ± 6.79	2.07 ± 0.15
t	13.2***	33.7***	–9.2***	–11.3***	–15.5***	n.s.	–8.9***	64.8***	–9.1***	–18.9***

[a] AC: Alicante Control; AR: Alicante with wastewater irrigation; MC: Monforte Control; MR: Monforte with wastewater irrigation; B1C: Biar 1 Control; B1R: Biar 1 with wastewater irrigation; B2C: Biar 2 control; B2R: Biar 2 with wastewater irrigation. SOC: soil organic carbon; EC: electrical conductivity; CEC; cation exchange capacity; P: available phosphorus; WHC: water holding capacity; AS: aggregate stability. PNP: p-nitrophenol. Different letters indicate significant differences. (Significant at: $P<0.05 = *$, $P<0.01 = **$, $P<0.001 = ***$, n.s. = not significant = $P>0.05$)

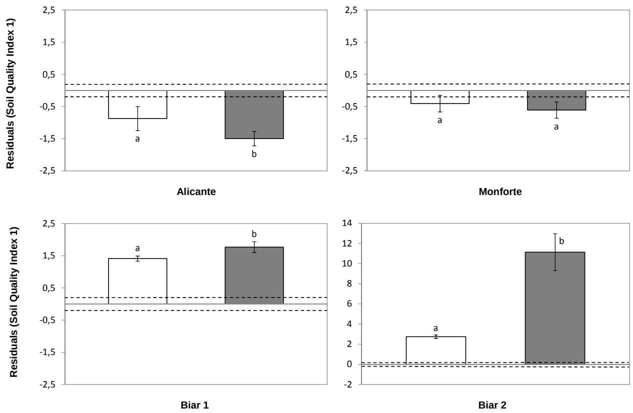

Fig. 2. Soil quality index 1 for each of the study sites. Dash lines limit 95 % confidence interval of calibration (–0.21, +0.21). Controls are indicated with white colour bars and irrigated with wastewaters with dark grey colour. Different letters indicate significant differences between means at ($P<0.05$) after T-Student test. Error bars denote standard deviation.

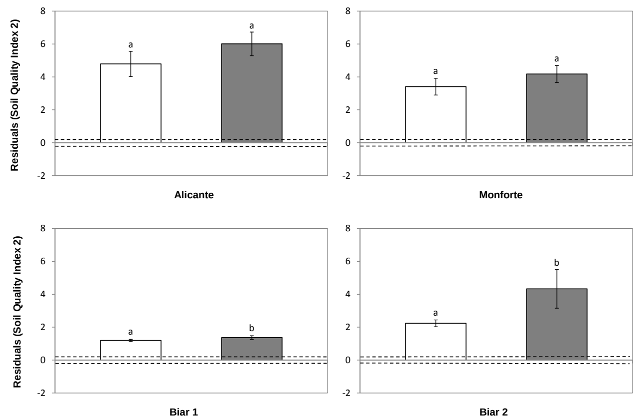

Fig. 3. Soil quality index 2 for each of the study sites. Dash lines limit 95 % confidence interval of calibration (–0.23, +0.23). Controls are indicated with white colour bars and irrigated with wastewaters with dark grey colour. Different letters indicate significant differences between means at ($P<0.05$) after T-Student test. Error bars denote standard deviation.

and all the enzymatic activities analysed were higher in the soils irrigated with wastewater in this area.

3.2 Application of the soil quality indices (SQI)

Residuals have been calculated and represented by different graphs for each area of study. SQI 1 is showed in Fig. 2 and SQI 2 in Fig. 3. In none of the agricultural soils of the study, SOCc was similar to SOCa, the residuals of two models being over the limits of calibration for all of the study sites, indicating disequilibrium among soil properties in all cases.

3.2.1 Application of SQI 1

Residuals for model 1 of all the study sites showed disequilibrium among soil properties, this unbalanced situation being lower for Monforte site (MC: –0.40 and MR: –0.61). The disequilibrium in soils irrigated with wastewater was moderately higher than their respective controls. The highest value for SQI 1 was obtained in Biar 2 site (B2R: 11.14 and B2C: 2.74), the mean values of SQI 1 for the Alicante site were: –0.87 (AC) and –1.49 (AR), and for the Biar 1 site were: 1.41 (BC) and 1.76 (BS).

3.2.2 Application of SQI 2

All soils in the study showed positive residuals for SQI 2 and a higher confidence interval than established for the equilibrium. There were statistical differences between treatments for each study site, soils with wastewater irrigations showing higher residuals values than soils with fresh water irrigation. For this model, Biar 1 showed the lowest residuals (B1C: 1.19 and B1R: 1.37) and maximum values were for Alicante site (AR: 6.10 and AC: 4.78). The values of SQI 2 in the Monforte site were: 3.41 (MC) and 6.00 (MR), in Biar 2 area were: 2.23 (B2C) and 4.33 (B2R).

4 Discussion

Some changes in the studied soil properties were found in A, M and B1 sites as a consequence of the use of wastewater, (Table 2) although in general terms these changes were not quite relevant in absolute values due to the good quality of treated wastewater used for the irrigation in those cases (Russan et al., 2007). In soils of B1 area an increase of the electrical conductivity was observed as a consequence of the irrigation with treated wastewater; although at the moment of sampling this value was not high, it could be a risk in the long-term for soil, as it indicates an increase of the saline concentration. As a consequence, electrical conductivity of water must be periodically controlled to avoid undesirable effects (Morugán-Coronado et al., 2011). The observed marked differences in the soils from B2 site are due to the characteristics of the wastewater used, which was almost untreated and, therefore, rich in organic compounds in this case. The long-term irrigation with this type of water caused a high increase of soil organic matter content (Jueschke et al., 2008) and as a consequence other properties such as AS, enzymatic activities, etc. Also in this case the value of EC reached showed an important increase in soil salinity.

The application of the soil quality indices indicated that the use of soil for agriculture caused a disturbance in its natural balance in the four different sites. Other authors verify that soil tillage and fertilisation caused an disequilibrium situation between organic matter content and other soil properties (Karlen et al., 1994; Hussian et al., 1999; Wander and Bollero, 1999; Zornoza et al., 2008).

Many studies have elaborated soil quality indices in agroecosystems using different indicators (Caravaca et al., 2002; Bastida et al., 2006). These indices are generally useful to classify the soils according to their degree of alteration, evaluating the effects of management, the crop yield and quantifying the long-term effects of different fertilisers (Glover et al., 2000; Caravaca et al., 2002; Masto et al., 2007). Leirós et al. (1999) verified the usefulness of application of quality indices to differentiate between different levels of degradation and the changes of soil physical, chemical and biochemical properties (Burke et al., 1995).

In our study, the areas irrigated with wastewater (A, B1 and B2) showed higher residuals values than areas irrigated with fresh water. B2R, the area with highest values for the studied soil properties, was the site with maximum residuals values at both SQI that it could means the alteration in this area is more severe than the other sites. Similar results were found by Puglisi et al. (2006) in soils with intensive agricultural exploitation, municipal and industrial wastes amendments and in soils irrigated with saline waters, which showed higher residuals values than native soil with climax situation.

The Monforte site was closer to the interval of confidence established with SQI 1 than the other sites of our study; these results, near the limits of calibration, could indicate a slight recovery of equilibrium in soil properties, that may be attributable to a better management of agricultural practices during a long-term period (more than twenty years with the correct irrigation and right management). SQI 1 could be appropriate for assessing severe states of degradation, like in the case of B2R site, due to its susceptibility to detect changes in physical and chemical properties of soil (Filip, 2002; Reynolds et al., 2002).

SQI 2 is more sensitive than SQI 1, owing to the high sensitivity to biochemical indicators (enzyme activities) (Nannipieri et al., 1990; Dick et al., 1996; Van Brugger and Semenov, 2000). Biochemical properties, such as soil enzymatic activities, change more quickly than physical properties. Caravaca et al. (2002) demonstrated the alteration of enzymatic activities due to agricultural practices and evaluated the effects of management and land use on enzymatic activities; they concluded that altered soils showed higher residuals values than control soils. García-Ruíz et al. (2008) revealed that intensive tillage has a tendency to delay any progress in soil quality. In contrast, Bergstrom et al. (1998) focused on the effects of tillage on enzymatic activities in an agricultural soil and the response was not consistent. In our case the residual values of SQ2 were higher than those obtained for SQ1, pointing to its higher sensibility to soil disturbances. The results confirm that SQI 1 more clearly evidences severe state of degradation, while SQI 2 is more adequate to indicate initial or fast perturbations in soil.

The soil quality indices used in our research (Zornoza et al., 2007b) have revealed the high level of disturbance in these Mediterranean agricultural soils. Tillage practices are generally considered to be the major cause of soil degradation and it has also been confirmed that agricultural management has caused a disruption in the natural equilibrium of soils (Kieft, 1994; Gardi et al., 2002). Continuous soil tillage and fertilisation have led to a disturbed situation between organic carbon and other soil properties.

5 Conclusions

The results of our study showed that only in the case of very low wastewater quality and its long-term application, relevant changes in soil properties can be produced.

The application of the soil quality indices showed that all of the soils of the agricultural study sites are in a situation of disequilibrium with respect to the relationships between their properties and independently of the water used for irrigation. The differences of the residuals of the soil quality indices among irrigated with wastewaters and their controls were low, except for the case of the site where there was low quality of wastewater and a long-term application.

The soil quality indices seem to be useful to differentiate between degraded status in agricultural soils, and can be used in monitoring and assessing the best agricultural managements and water for irrigation. Nonetheless, it is necessary to validate these indices in other soils and sites, and it could also be interesting to validate their use for other potential causes of degradation, such as contamination, salinisation, compactation, management practices, etc., or how they respond to distinct practices of soil recovery. This validation would also be required to determine the precise suitability of each model for a concrete cause of degradation.

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