

Abstract

The supply of water is limited in some parts of the Mediterranean region, such as south-eastern 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, the equilibrium reached 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. This study was carried out in three areas of Alicante Province (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 rapid development of agricultural and touristic activities and fast expansion of the industrial sector which have produced an over-exploitation of aquifers. For this reason,

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could provoke alteration in some soil properties (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 indice 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.

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.

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 during 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 during 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 2 ha plot that has been used as a “green filter” during 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).

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 ($\sim 25^{\circ}\text{C}$) for a week. After that, they were sieved to 2 mm for analyses,

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except for aggregate stability soil samples aliquots were sieved between 4–0.25. For all analysis, 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, and its relationships between soil parameters. 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 (*P*), 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 β -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 (*P*_m) of each study site as an independent variable in the regressions, divided in two categories (*P*_m < 350 mm and *P*_m > 350 mm). The selection of category was in function of *P*_m for each area (Table 1). Therefore, there are two equations for both models, exposed below; the first formula (A and C) corresponds

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to multiple linear regression for soils with $P_m < 350$ 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 $P_m > 350$ mm, in this study both the sites located in Biar. In these equations: SOC is expressed in g kg^{-1} , phosphatase and β -glucosidase activities in $\mu\text{mol p-nitrofenol g}^{-1} \text{h}^{-1}$, urease activity in $\mu\text{mol NH}_4^+ \text{g}^{-1} \text{h}^{-1}$, WHC and AS in %, P in mg kg^{-1} , EC in $\mu\text{S cm}^{-1}$ and CEC in $\text{cmol}^+ \text{kg}^{-1}$.

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

$$\text{Ln (SOC)} = A(\text{for } P_m < 350 \text{ mm}); \text{ or } \text{Ln (SOC)} = A + B \text{ (for } P_m < 350 \text{ mm)} \quad (1)$$

$$A = 2.459 + 0.090 (\text{phosphatase}) + 0.010 (\text{WHC}) + 0.001 (\text{EC}) - 0.009 (P) + 0.012 (\text{CEC}) + 0.001 (\text{AS})$$

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

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:

$$\text{Ln (SOC)} = C \text{ (for } P_m < 350 \text{ mm}); \text{ or } \text{Ln (SOC)} = C + D \text{ (for } P_m < 350 \text{ mm)} \quad (2)$$

$$C = 5.527 + 0.150 (\text{phosphatase}) - 0.064 (\text{Urease}) - 0.088 (\beta - \text{glucosidase}) - 0.291(\text{pH}) + 0.001(\text{EC}) + 0.028 (P) + 0.028 (\text{CEC})$$

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

This model explains de 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

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be lower or higher than the actual SOC, and degraded soils should generate residuals with values <0 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:

$$\text{SQI} = \text{model residual} = \text{SOCc} - \text{SOCa}$$

$$\text{SQI 1} = \text{model 1 residual} = \text{SOCc} - \text{SOCa}$$

$$\text{SQI 2} = \text{model 2 residual} = \text{SOCc} - \text{SOCa}$$

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 <0 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 (P) 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 Bremner (1969). The activity of β -glucosidase was determined according to Tabatabai (1982).

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The major differences observed due to the irrigation with wastewater for the studied properties were in the soils from Biar 2 site. All the parameters analyzed 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, also the EC has increased more than twice from its initial values. The same behaviour was observed for the percentage of stable aggregates, and all the enzymatic activities analyzed 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 figure 2 and SQI 2 in figure 3. In not one 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

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Many studies have elaborated soil quality indices in agro-ecosystems using different indicators (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).

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 evaluated 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). 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. 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 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 Bruggen and Semenov, 2000). Biochemical properties, such as soil enzymatic activities, change

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, salinization, 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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Table 1. Sites, irrigation, climate and soil characteristics.

Site ^a	Water type used ^b	Period of irrigation (years)	Irrigation method	T _m ^c (°C)	P _m ^c (mm)	Soil Type (SSS, 2010)	Texture ^d (% sand, silt clay)	OM ^e (%)	pH	CaCO ₃ (%)
AC	FW	40	Drip			Xerorthent	Silty loam (1,56,41)	3.8	8.3	53
AR	WW	40	Drip	17.9	301	Xerorthent	Silty clay loam (7,76,15)	5	7.9	54
MC	FW	20	Drip			Xerorthent	Clay loam (56,22,21)	3.2	8.3	46
MR	WW	20	Drip	18.3	335	Xerorthent	Clay loam (56,19,23)	4.5	8.1	48
B1C	FW	2	Flooding				Silty clay loam (29,44,25)	2	8.6	42
B1R	WW	2	Flooding	14.5	486	Xerofluvent	Clay loam (26,44,29)	2	8.9	43
B2C	–	–	–				Sandy clay loam (74,8,17)	1	8.7	25
B2R	WW	20	Flooding	14.5	486	Xerofluvent	Sandy clay loam (59,17,22)	8	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 (T_m) and mean annual precipitation (P_m). ^d Sand: 2–0.02 mm; silt: 0.02–0.002 mm; clay: <0.002 mm. ^e OM: organic matter.

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

Parameter	B1R	B2R	AR	MR
EC ($\mu\text{S cm}^{-1}$)	1915	4000	3088	1856
BOD ₅ ($\text{mg O}_2 \text{ l}^{-1}$)	13.5	337	13	19
COD ($\text{mg O}_2 \text{ l}^{-1}$)	59.6	819	52	74
SS (mg l^{-1})	18.5	207	22	19

EC: Electrical conductivity; BOD₅: biological oxygen demand; COD: Chemical Oxygen Demand; SS: suspended solids.

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

Site ^a	SOC g kg ⁻¹	pH	EC $\mu\text{S cm}^{-1}$	CEC cmol ⁺ kg ⁻¹	P mg kg ⁻¹	WHC %	AS %	Phosphatase $\mu\text{mol PNP g}^{-1} \text{h}^{-1}$	Urease $\mu\text{mol NH}_4^+ \text{g}^{-1} \text{h}^{-1}$	B-glucosidase $\mu\text{mol PNP g}^{-1} \text{h}^{-1}$
AC	22 \pm 4	8.3 \pm 0.1	412 \pm 28	10.2 \pm 0.9	163.4 \pm 29.3	52 \pm 3	40 \pm 16	1.52 \pm 0.46	7.54 \pm 1.63	1.96 \pm 0.41
AR	30 \pm 2	7.9 \pm 0.1	496 \pm 83	9.8 \pm 1.0	213.8 \pm 27.4	52 \pm 3	58 \pm 16	2.29 \pm 0.37	9.29 \pm 1.78	2.18 \pm 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 \pm 4	8.3 \pm 0.1	339 \pm 61	6.1 \pm 0.6	109.8 \pm 19.8	50 \pm 2	45 \pm 5	1.20 \pm 0.32	4.83 \pm 0.97	1.58 \pm 0.46
MR	26 \pm 2	8.1 \pm 0.1	478 \pm 97	7.6 \pm 1.6	133.4 \pm 9.9	55 \pm 8	39 \pm 10	1.92 \pm 0.81	4.89 \pm 1.02	1.12 \pm 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 \pm 1	8.6 \pm 0.1	186 \pm 24	5.5 \pm 0.3	14.2 \pm 1.5	50 \pm 3	49 \pm 5	0.60 \pm 0.09	1.60 \pm 0.44	0.49 \pm 0.08
B1R	12 \pm 1	8.9 \pm 0.1	359 \pm 33	5.9 \pm 0.8	19.7 \pm 3.9	49 \pm 6	42 \pm 8	0.63 \pm 0.09	1.50 \pm 0.35	0.54 \pm 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 \pm 1	8.9 \pm 0.1	76 \pm 9	1.0 \pm 0.2	19.3 \pm 1.9	27 \pm 2	36 \pm 13	0.28 \pm 0.08	5.93 \pm 3.79	0.41 \pm 0.16
B2R	88 \pm 16	7.8 \pm 0.1	160 \pm 20	18.0 \pm 3.7	234.9 \pm 34.0	25 \pm 7	85 \pm 1	3.31 \pm 0.81	34.83 \pm 6.79	2.07 \pm 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 = $P > 0.05$)

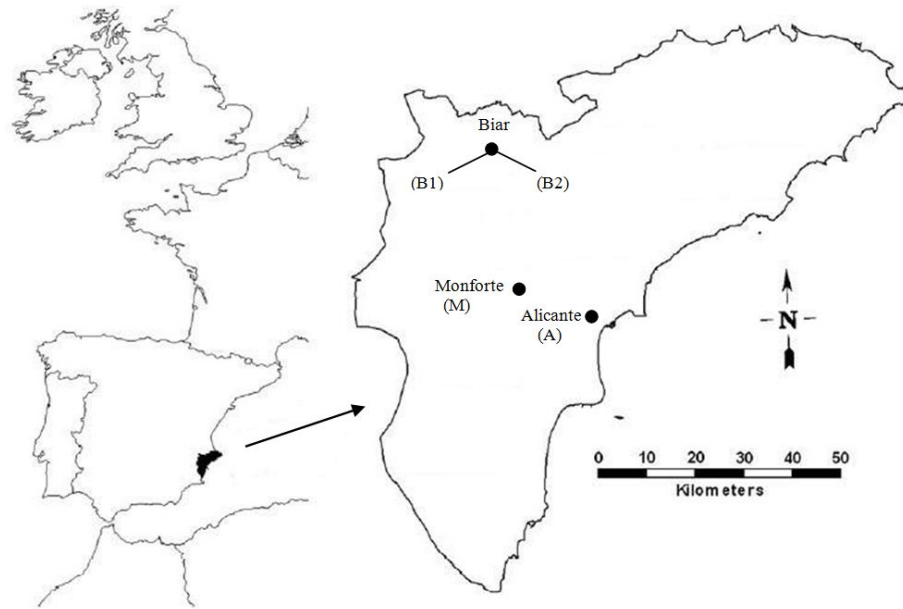


Fig. 1. Location of the study sites.

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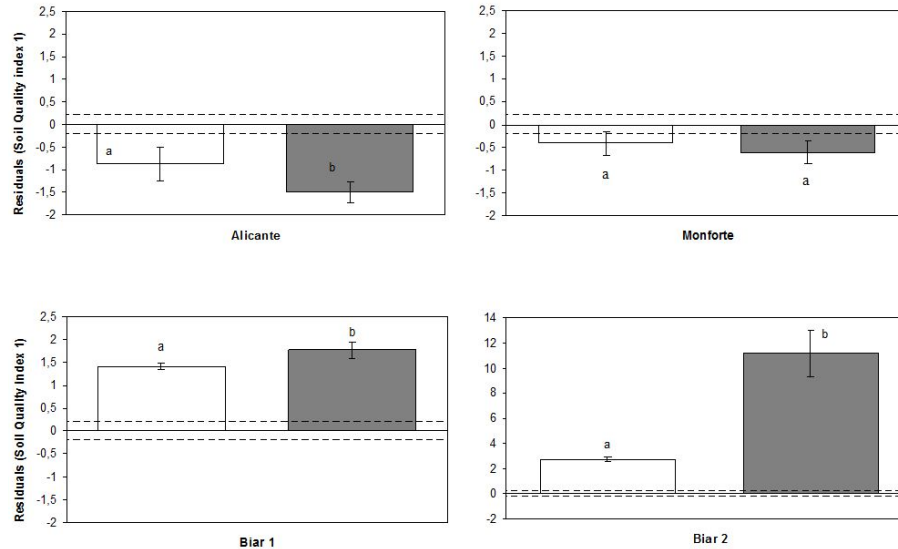


Fig. 2. Soil quality index 1 for each of the study sites. Dash lines limit 95% confidence interval of calibration (-0.21 , $+0.21$). Controls are indicated with white color bars and irrigated with wastewaters with dark grey color.

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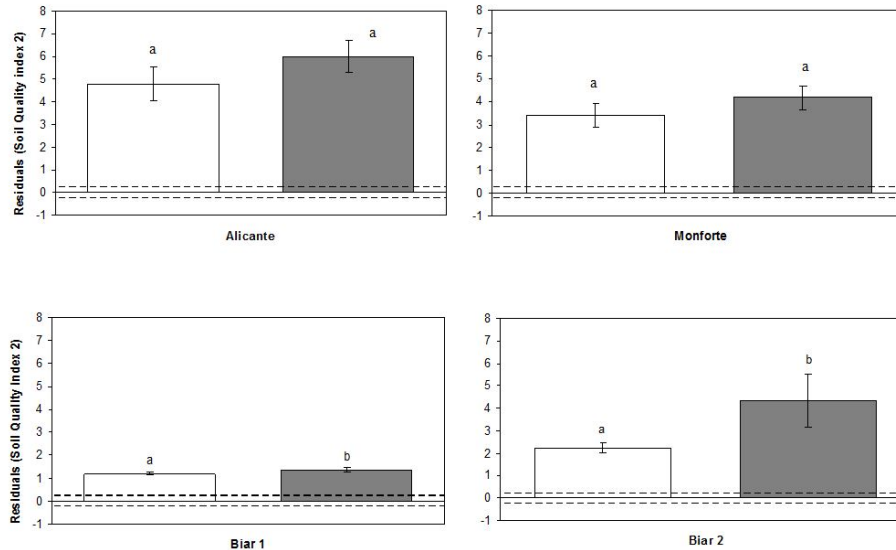


Fig. 3. Soil quality index 2 for each of the study sites. Dash lines limit 95% confidence interval of calibration (-0.23 , $+0.23$). Controls are indicated with white color bars and irrigated with wastewaters with dark grey color.

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