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Long-Term Effect of Organic and Mineral Fertilization on Soil Physical Properties Under Greenhouse and Outdoor Management Practices*[1]

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ABSTRACT

To evaluate the use of organic amendments as an alternative to conventional fertilization, a 10-year experiment on a loam soil was conducted under a crop rotation system in both greenhouse and outdoor plots applied with chemical fertilizers (NPK) and vegetal compost (organic fertilizer) in the Guadalquivir River Valley, Spain. The effect of these two different fertilization regimes on the soil physical properties was evaluated. Soil organic carbon (OC), soil bulk density (BD), soil water retention (WR), available water content (AWC), aggregate stability (AS), and soil physical quality (Dexter's index, S) were determined. The use of organic fertilizer increased OC and resulted in a significant increase in AS and a decrease in BD compared to the mineral fertilizer application in both greenhouse and outdoor plots. The outdoor plots showed the lowest BD values whereas the greenhouse plots showed the highest AS values. In the last years of the 10-year experiment the S parameter was significantly higher in organic fertilizer plots, especially for greenhouse plots. At the end of the study period, there were no significant differences in WR at field capacity (FC) between treatments in both systems; the AWC was also similar in the greenhouse plots but higher in the mineral outdoor plots. In mineral fertilizer treatments, a small improvement in the physical properties was also observed due to the utilization of less aggressive tillage compared with the previous intensive cropping system. Physical soil properties were correlated with soil OC. The sustainable management techniques such as the use of organic amendments and low or no tillage improved soil physical properties, despite the differences in management that logically significantly affected the results.

Key Words: aggregate stability, bulk density, organic matter, vegetal compost, water retention

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INTRODUCTION

Conventional agricultural practices may include frequent and intensive tillage and the extensive use of fertilizers and pesticides. Such practices can result in a loss of organic matter (OM), leading to the degradation of cultivated soils and a decline in soil quality (Reeves, 1997; Mitchell *et al.*, 1999; Peigné *et al.*, 2007). Therefore, it is necessary for soil OM content to be maintained or, where possible, increased, because it plays a fundamental role in soil processes that maintain productivity, replenish nutrients removed by crops, and enhance the desirable soil physical condition and biological activity (Watson *et al.*, 2002).

It is well established that the addition of OM improves the physical properties of soil (Bolvin *et al.*, 2009; Ruehlmann and Körschens, 2009) that are desirable for adequate plant growth. The increase in soil organic carbon (OC) reduces bulk density (BD) and increases water holding capacity and soil aggregate stability (AS) (Carter and Stewart, 1996; Celik *et al.*, 2004; Herencia *et al.*, 2008). Nevertheless, the effects of OM additions on the physical properties of soils depend on climate, soil characteristics, crop management, and the rate and type of organic amendments. Zhang *et al.* (2006) indicated that changes in soil water retention (WR) may depend more on the soil type and the initial OM content than on the addition of OM.

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Although an increase in OC is usually beneficial for improving physical properties, especially in Mediterranean soils that are low in OC, it is necessary to control such additions because more is not always better. For example, too much OC can result in surface crusting, decrease hydraulic conductivity (Haynes and Naidu, 1998), and increase water-repulsion (Olsen *et al.*, 1970).

In addition, most published studies refer to farm fields and have been conducted over periods of only several years, but there are few long-term studies that have been conducted in greenhouses. In general, many studies show the effect of additions of sewage sludge, urban waste compost, manure or agroindustrial residues on the physical properties of soil (Aggelides and Londra, 2000; Stepkowska *et al.*, 2001; Bastida *et al.*, 2007; Tejada *et al.*, 2007). Very few agronomic studies have been conducted in which green waste compost was applied (Chambers *et al.*, 2002; Tejada *et al.*, 2009).

The aim of this work was to determine the influence of organic *versus* mineral fertilization on the OM content and physical properties including the BD, WR, soil physical quality (Dexter's index, S), available water, and AS of a calcareous soil over a 10-year period under two different management practices, on the both greenhouse and outdoor plots.

MATERIALS AND METHODS

The field study was carried out on a loam soil classified as Xerofluvent (Soil Survey Staff, 1999) with high carbonate content. The study site (37° 8′ 33″ N, 5° 16′ 4″ W) was located in the Guadalquivir River Valley (SW Spain), at the Andalusian Institute of Agricultural Research "Las Torres-Tomejil" Farm in Alcalá del Río, Seville, Spain.

Two crop rotational systems under organic (Regulation (EEC) No. 2092/91) and mineral fertilization were carried out for 10 years beginning in 1997 in a greenhouse erected over the soil as well as in outdoor plots. Four replicates of each mineral and organic fertilizer plot were established randomly in the greenhouse and outdoors, and each plot was divided into three subplots (G1, G2, G3) of 3 m × 4 m in the greenhouse and three subplots (P1, P2, P3) of 6 m × 12.5 m in the outdoor plots, with different crops planted simultaneously in each subplot in order to have biodiversity in the system. The crops were planted in parallel in the both mineral and organic fertilizer plots to achieve spatial and temporal crop variability. In organic farming there is a major limitation to fertilization and pest and disease management. Therefore, the rotations of different crops on the same soil are essential for better use of nutrients and to break the cycle of biological pests. Another important aspect is the availability of a greater variety of species at the same time to promote biodiversity in the system to prevent the proliferation of pests. This causes the complexity in designing the crop rotation scheme. In the greenhouse the following crops were grown in the rotation system: bean (*Phaseolus vulgaris* L.), beetroot (*Beta vulgaris* L.), carrot (*Daucus carota* L.), chard (*Beta Vugaris* L.), cucumber (*Cucumis sativus* L.), marrow (*Cucurbita pepo* L.), pepper (*Capsicum annuum* L.), and tomato (*Lycopersicon lycopersicum* L.). In outdoor plots the following crops were grown: broad bean (*Vicia faba* L.), beetroot (*Beta vulgaris* L.), carrot (*Daucus carota* L.), cauliflower (*Brassica oleracea* L.), lettuce (*Lactuca sativa* L.), leek (*Allium porrum* L.), marrow (*Cucurbita pepo* L.), melon (*Cucumis melo* L.), peppers (*Capsicum annuum* L.), potato (*Solanum tuberosum* L.), strawberry (*Fragaria* L.), tomato (*Lycopersicon lycopersicum* L.), and watermelon (*Citrullus lanatus* L.)

Before each crop was sown or planted, the soil received different doses of compost depending on the soil OM content, compost characteristics and required fertilization by the crops, or a conventional mineral fertilizer. The organic fertilizer included composted vegetable residues from the experimental farm (residues of previous crops, grass, and residues from pruning fruit trees). The most relevant compost characteristics are shown in Table I.

TABLE I

Physico-chemical characteristics of the vegetal compost[a)] (on dry weight basis) added to the organic fertilizer plots

pH[b)]	EC[c)]	OC[d)]	N	P	K	Ca	Mg	Na	Fe	Mn	Cu	Zn
	dS m^{-1}	g kg^{-1}								mg kg^{-1}		
7.7±0.2[e)]	2.6±1.3	183±32	9.0±1.3	5.8±1.4	3.6±1.2	118±22	5.9±2.3	1.0±0.3	8.4±1.3	270±40	18.7±2.3	55.5±5.3

[a)]The humidity is 26%±3%; [b)]1:25 compost/water extract; [c)]Electrical conductivity; [d)]Organic carbon; [e)]Mean ± standard deviation ($n = 10$).

In each crop cycle, the organic fertilizer plots received 20 to 30 t ha^{-1} of the vegetal compost on a wet basis. In conventional plots, the doses of the inorganic fertilizer were based on soil analysis and agronomic recommendations for each crop in the zone (Maroto, 1995). The commercial fertilizers were ammonium nitrate ($N-P_2O_5-K_2O$: 33.5-0-0), poly-feed® fertilizer (20-5-32), potassium nitrate (13-0-46), and ammonium phosphate (12-60-0).

No tillage was implemented in the greenhouse, the organic amendment was applied to the soil surface and the mineral fertilizer through the drip irrigation system. The outdoor plots were shallow chisel ploughed in both treatments after each crop harvest, so the organic amendment was incorporated into the soil. Harvest residues were left on the surface as mulch in the greenhouse and incorporated into the outdoor plots. However, before initiating the study, the plots were cultivated under more intense tillage (mouldboard ploughing at more than 35-cm depth) frequently.

In the greenhouse, all crops were irrigated by drip irrigation. The outdoors plots were irrigated by surface irrigation and water was supplied weekly through furrow irrigation. Irrigation is scheduled by use of a Class A evaporation pan. Only the melons and watermelons were irrigated by drip irrigation system. The area has an annual rainfall of 650 mm, an average temperature of 18 °C and 4 mm of average daily evaporation.

At the beginning of the experiment, the soil was uniform in physico-chemical properties as indicated by the small standard deviation of the data (Table II). This implied that any chemical and physical soil differences experienced during the project may be attributed to the treatment rather than the soil heterogeneity.

For chemical analysis, three soil cores from the upper horizon (0–15 cm) were randomly collected at the end of each crop period from each subplot to make a composite sample. The chemical properties of vegetal compost and soil shown in Tables I and II, respectively, were determined using the official methods of MAPA (1994). For the OC determination, air-dried and sieved (< 2 mm mesh size) soil was analysed by oxidizing with K_2CrO_7 in an acid medium and evaluating the excess of the dichromate with $(NH_4)_2Fe(SO_4)_2$ (Yeomans and Bremner, 1989).

For the physical properties, both in the greenhouse and in the outdoor plots, soil samples were collected four times: at the beginning of the experiment (autumn 1997), spring 2001, autumn 2004, and the end of the study (spring 2007). BD was determined from undisturbed soil cores from the upper horizon (0–15 cm) according to Henin *et al.* (1972). For the soil WR, gravimetric water content was determined in undisturbed soil cores using a pressure plate apparatus at 0, −5, −10, −33, −50, −100, −300, and −1 500 kPa water potentials (Klute, 1986). At each pressure, soil samples were equilibrated for 48 h, weighed, and returned to the plate extractor for the next pressure step. After the final pressure, the soil samples were oven-dried at 105 °C during 24 h to determine the volumetric water content. The −10 kPa simulated the water content of soil at field capacity (FC) and −1 500 kPa represented the permanent wilting point (PWP). The difference between water retained at −10 and −1 500 kPa matric potentials is the available water content (AWC).

The mean water contents for every value of suction were then fitted to the equation given by van Genuchten (1980), using RETC (Retention Curve Program for Unsaturated Soils) software (van Genuchten *et al.*, 1991) to calculate the Dexter's index, S, of soil physical quality proposed by Dexter (Dexter, 2004a, b).

$$\theta = (\theta_{\mathrm{SAT}} - \theta_{\mathrm{RES}})[1 + (1 + \alpha h)^n]^{-m} + \theta_{\mathrm{RES}} \quad (1)$$

where θ is the volumetric water content; θ_{SAT} and θ_{RES} are the saturation and residual water contents, respectively; h is the soil water pressure; α is a scale factor for water potential; and m and n are the parameters that define the shape of the curve. Dexter's index, S, is the absolute value of the slope of the curve at the inflection point obtained when gravimetric water contents are

TABLE II

Soil physico-chemical characteristics at the beginning of the experiment in 1997

Sand	Silt	Clay	pH[a)]	EC[b)]	CEC[c)]	$CaCO_3$	OM[d)]	N[e)]	Available P	Available K
	g kg^{-1}			dS m^{-1}	$cmol_c$ kg^{-1}		g kg^{-1}		mg kg^{-1}	
285±18[f)]	458±38	257±21	8.2±0.1	0.22±0.02	14.9±0.3	218±13	13.1±1.0	0.79±0.10	26.0±3.4	171.2±11.2

[a)]1:2.5 soil/water extract; [b)]Electrical conductivity; [c)]Cation exchange capacity; [d)]Organic matter; [e)]Kjeldahl-N; [f)]Mean ± standard deviation (n = 15).

plotted against the natural logarithms of the matric tensions (Dexter, 2004a):

$$S = -n(\theta_{\mathrm{SAT}} - \theta_{\mathrm{RES}})[(2n-1)/(n-1)]^{-(1/n-2)} \quad (2)$$

Critical S values were tentatively suggested by Dexter (2004a): $S > 0.035$ was established to indicate favourable soil physical conditions for root growth; $S = 0.020$–0.035 is considered to be not very favourable (little root growth) and $S < 0.20$ is considered highly restrictive (no root growth).

Soil AS was determined for an aggregate size fraction of < 2 mm according to Henin *et al.* (1972). The aggregate size fraction of < 2 mm was used. The proportions of the aggregates that were stable to pretreatments with water, ethanol, and benzene were calculated, and the instability index (Is) was obtained using the equation:

$$\mathrm{Is} = \frac{(\% < 20\,\mu\mathrm{m})_{\max}}{(\mathrm{Ag} + \mathrm{Ag_a} + \mathrm{Ag_b})/3 - 0.98(\%\mathrm{CS})} \quad (3)$$

where $(\% < 20\ \mu\mathrm{m})_{\max}$ is the largest proportion of the clay and silt fraction at < 0.02 mm; $\mathrm{Ag} + \mathrm{Ag_a} + \mathrm{Ag_b}$ represent the sum of the stable aggregates at > 0.25 mm (%) in water, ethanol, and benzene, respectively, obtained by sieving with the Feódoroff (1960) apparatus, and %CS is the largest proportion of the coarse sand (0.2–2 mm fraction) forming part of the stable aggregates. Higher Is values indicate lower soil AS. The structural stability (log 10 Is) was classified according to the Baize (1988) criteria: very stable (< 1.0), stable (1.0–1.3), slightly stable (1.3–1.7), unstable (1.7–2.0), and very unstable (> 2.0).

Statistical analyses were carried out using the program SPSS 11.0 for Windows and the results were expressed as mean values. Significant differences between management systems were found by the student's t-test at $P < 0.05$. A correlation matrix of different properties was based on Pearson correlation coefficients ($P < 0.01$ and $P < 0.05$).

RESULTS AND DISCUSSION

Organic carbon

The soil OC content exhibited significant differences in the organic fertilizer plots compared with those receiving mineral fertilizer, for both the greenhouse and the outdoor plots (Fig. 1). Certain cycles are not present in this figure because no samples were collected, because they represented a continuation of the previous crops or because there were no crops. For the last cycle in the greenhouse, the mean OC value for the organic fertilizer treatment was 19.07 g kg^{-1}, whereas for the mineral fertilizer treatment the mean value was 6.89 g kg^{-1}. These differences were statistically different ($P < 0.01$). In contrasts, the mean values for the outdoor plots were 14.73 and 6.36 g kg^{-1} in organic and mineral fertilizer plots, respectively, which were significantly different ($P < 0.01$). At the beginning of the experiment, soil for both types of fertilization treatments was similar. From the second year of this study (1998) till the end, differences in OC content between the organic and mineral fertilizer plots were evident. In addition, the OC values in the mineral fertilizer plots were almost constant over the course of the study, especially in the case of the greenhouse plots (Fig. 1). In

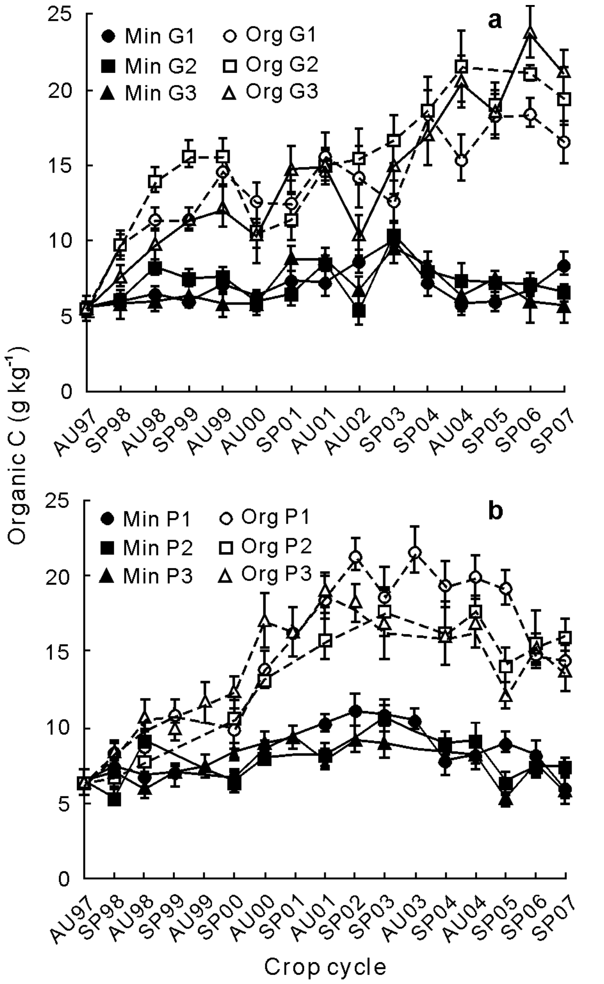

Fig. 1 Values of soil organic carbon in the (a) greenhouse (G1, G2, G3) and (b) outdoor (P1, P2, P3) plots applied with mineral (Min) and organic (Org) fertilizers during different cultivation cycles ranging from autumn (AU) 1997 (97) to spring (SP) 2007 (07). Error bars represent standard deviations of the means ($n = 4$).

the organic systems, the OC values showed an increase over the course of the study and showed a tendency to stabilize in the last cycles. Thus the use of green waste compost showed an increase in the OC compared to mineral fertilization, in the outdoor as well as the greenhouse plots. According to Peigné *et al.* (2007), the combined action of conservation tillage and the input of fresh OM such as leguminous residues increased the soil organic C. Despite the great differences in greenhouse and outdoor plots management that significantly affected the results, both increased the OC content and it is generally accepted that the increase of soil organic matter improve soil physical properties.

Bulk density

At the beginning of the study, no differences were found in BD between the organic and the mineral fertilizer plots in the greenhouse (Fig. 2) with a mean value of 1.54 Mg m^{-3}. In the greenhouse, the BD showed a continuous decrease through the ten years of study. At the end, the BD in the organic fertilizer plots was significantly lower than that in the mineral fertilizer plots. For the organic fertilizer treatment, the mean value was 1.24 Mg m^{-3}; whereas it was 1.36 Mg m^{-3} for the mineral fertilizer treatment. These differences were statistically significant ($P < 0.05$) (Fig. 2). It is interesting to note that there was also a decrease in the BD of the mineral fertilizer plots across the study in comparison to the original values.

At the end of the study, in the outdoor plots, the BD also was found to be lower in the organic fertilizer plots compared to plots receiving mineral fertilizer. In both cases, the values were lower than the original ones (Fig. 2). At the end of the experiment, the mean value was 1.20 Mg m^{-3} for the organic fertilizer treatments and 1.34 Mg m^{-3} for the mineral fertilizer treatments. These differences were statistically significant ($P < 0.05$). In the outdoor plots, the decrease was greater than in the greenhouse, mainly in the first years in both the organic and the mineral fertilizer plots. At the end of the study, the differences in BD values between treatments were similar for the greenhouse and outdoor plots, but the system evolution was different. The differences between treatments, fundamentally tillage, could explain the differences. It is known that the OM improves soil structure. Possibly in low tillage the OM is incorporated faster in the top few centimeters of soil than in non-tillage, accelerating the beneficial effects of OM on the structure, as in the case of outdoor plots. However, over time, the OM in low tillage is more available for microorganisms and it is mineralized more quickly than in no tillage, which could reverse the trend. So with no tillage being used in greenhouse, OM left on the surface may increase over the long term as corroborated by the data of OC (Fig. 1). Possibly, in the long term, no tillage is the best management to improve the soil structure.

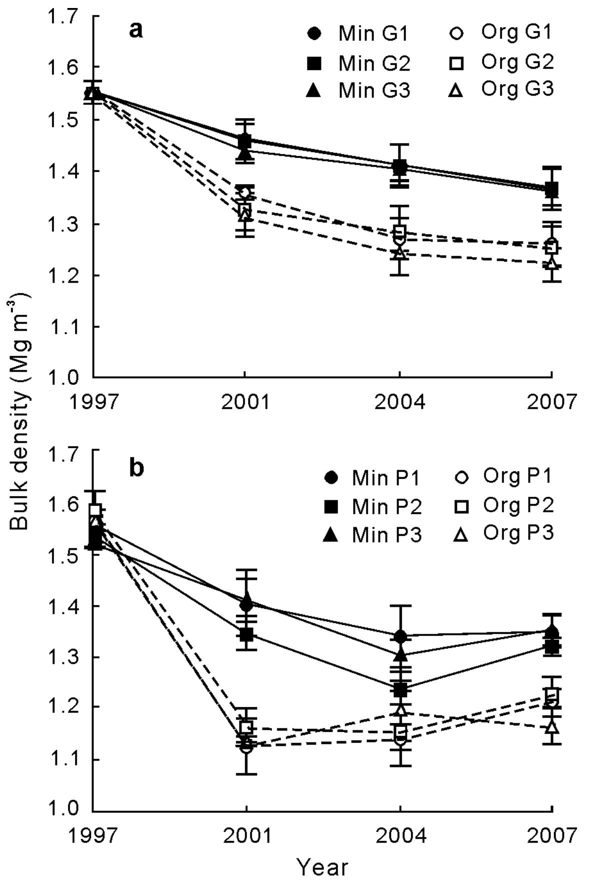

Fig. 2 Soil bulk densities in the (a) greenhouse (G1, G2, G3) and (b) outdoor (P1, P2, P3) plots applied with mineral (Min) and organic (Org) fertilizers at the beginning (1997), after four and seven years (2001 and 2004), and at the end of the study period (2007). Error bars represent standard deviations of the means ($n = 4$).

At the end of the experiment, the mineral fertilizer plots, and especially the organic fertilizer plots showed lower BD than the original soil. These findings can be explained by the fact that before the initiation of the study, the plots had been cultivated under more intense tillage. In our experience, both the mineral and the organic fertilizer plots were subjected to low or no tillage in outdoor and greenhouse plots, respectively, thus showing less compaction and consequently a lower BD. Low tillage and no tillage reduce the soils' susceptibility to compaction in silty-loam and loam soils (Blanco-Canqui *et al.*, 2009). The main underlying mechanism for the reduction in BD with an increase in soil OC content is the low density, high specific surface area, elastic properties, and high water absorbency of soil OM (Soane, 1990; Blanco-Canqui *et al.*, 2009).

Addition of organic amendment significantly increased soil OM contents and decreased soil BD, as found in previous studies (Haynes and Naidu, 1998; Zhang *et al.*, 2006). Mosaddeghi *et al.* (2000), in a study with soil characteristics similar to ours, found that an application of 50 Mg ha^{-1} reduced compaction of the soil. However, Colla *et al.* (2000) showed no changes in BD after OM additions for ten years, which is probably due to the use of more tillage in the organic fertilizer plots than in the mineral fertilizer plots.

Soil water retention

There were no differences in WR values at FC and PWP between the organic and the mineral fertilizer plots for greenhouse soils at the beginning (1997) of the study (Fig. 3a). In the autumn of 2004 the WR was significantly different between the treatments only at PWP, but there were no differences at the FC. However, at the end of the experiment (2007), there were no differences at FC and PWP.

In the outdoor plots, the trend was different from that of the greenhouse, and the differences between the organic and the mineral fertilizer treatments were less evident (Fig. 3b). At the beginning, the data showed no difference between the plots because all of them had been subjected to the same fertilization. In the spring of 2001 and the autumn of 2004 few differences in WR values can be seen. At the end of the experiment (2007), no differences appeared at FC, but there were differences at the PWP point.

In general, the data did not show differences in WR values between treatments in both systems except for some PWP values. In these cases the moisture contents at PWP were higher in organic fertilizer plots than in the mineral fertilizer plots (Fig. 3). Other studies found an increase in the WR with the application of organic amendment to the soil (Metzger and Yaron, 1987; Werner, 1997; Clark *et al.*, 1998). However, McVay *et al.* (2006) indicated that greater OC did not result in greater WR for the majority of the soils evaluated in their studies.

At the end of the study period there were no significant differences between the treatments except for water potentials. An increase in the WR at tensions of FC was mainly due to the augmentation of the number of small pores. At higher tensions near the PWP, almost all of the pores are air-filled, and the WR is determined by the surface area and the water film thickness on these surfaces (Khaleel *et al.*, 1981). After the OM addition, the area of the specific surface enlarges, resulting in an increase in WR at higher tensions (Gupta *et al.*, 1977). Our study showed different results for WR in the greenhouse and the outdoor plots in the last years. A possible explanation is that the differences in the management of both systems (*i.e.*, tillage/no tillage, irrigation systems) produced differences in the microbiological activity that influenced the aggregation, structure, and therefore the WR of the soil. More further studies on the relation of microbial biomass and soil physical properties are necessary.

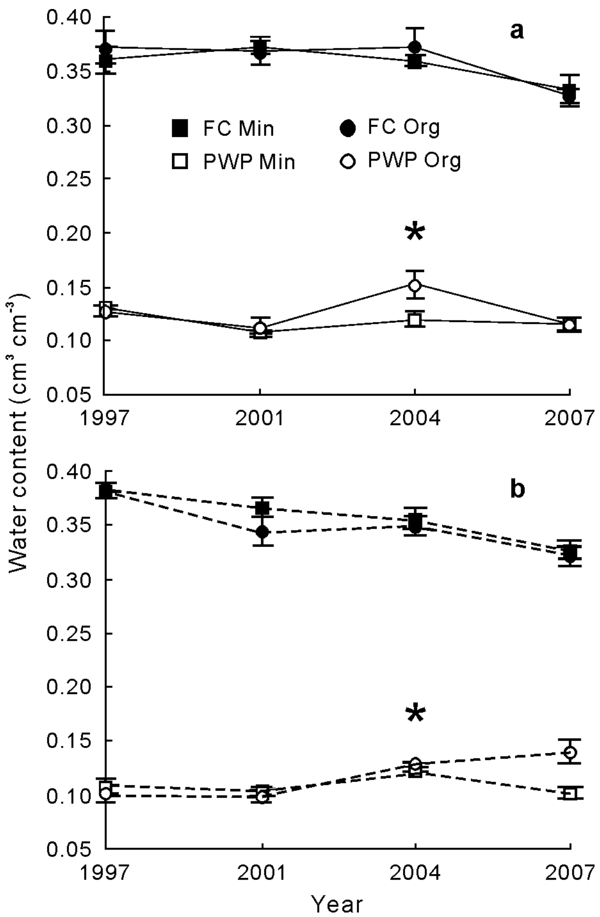

Fig. 3 Soil volumetric water contents at field capacity (FC) and permanent wilting point (PWP) conditions in the (a) greenhouse and (b) outdoor plots applied with mineral (Min) and organic (Org) fertilizers at the beginning (1997), after four and seven years (2001 and 2004), and at the end of the study period (2007). *Significant at $P < 0.05$. Error bars represent standard deviations of the means ($n = 12$).

Available water content

The AWC also showed differences in greenhouse and outdoor plots across the study (Fig. 4). At the end of the study, the AWC in the greenhouse plots was similar in organic and mineral fertilizer plots, but AWC was lower in organic than mineral fertilizer treatment in the outdoor plots. It is interesting to observe that the AWC decreased during the study for organic and mineral fertilizer plots in both systems.

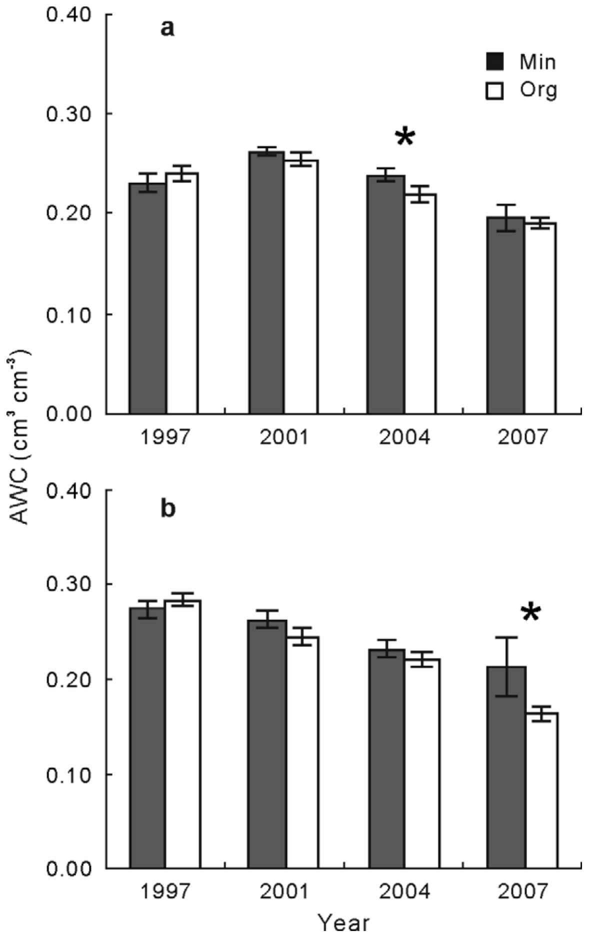

Fig. 4 Soil available water contents (AWCs) in the (a) greenhouse and (b) outdoor plots applied with mineral (Min) and organic (Org) fertilizers at the beginning (1997), after four and seven years (2001 and 2004), and at the end of the study period (2007). *Significant at $P < 0.05$. Error bars represent standard deviations of the means ($n = 12$).

The AWC is obtained from the differences in the WR at FC and PWP. In general, the application of OM and the increase in the WR in organic fertilizer plots provide more available water to plants (Shepherd *et al.*, 2002; Wesseling *et al.* 2009). In our study this was not so clear. We think that the differences in the AWC in both systems were mainly influenced by the differences in the BD. The greater decrease in the BD in the outdoor plots provoked the lower AWC in the organic fertilizer plots, and this decrease would be compensated by an increase in the frequency and amount of irrigation. The AWC is a theoretical determination obtained from the assumption that the water available to plants is the difference between the WR at FC and PWP (in these soils generally at −10 and −1 500 kPa, respectively), but this value is affected by the soil characteristics and plant physiology. On the other hand, the lower values of the BD allow for a higher development of the root systems, increasing the water availability to the crop. Batey (2009) reported that the compaction alters many soil properties and adverse effects are mostly linked to a reduction in permeability to air, water, and roots. In conclusion, we considered that the AWC might be an interesting but artificial and qualitative index that should be used with caution.

S values

Since the third sampling (autumn of 2004), there were evident differences between treatments in the S index in the outdoor as well as the greenhouse plots (Fig. 5). The S values of organic fertilizer plots were statistically higher than those of mineral fertilizer plots. The higher S values were found in the greenhouse plots.

Dexter (2004b) indicated that the greater S value resulted in better physical soil quality. The author also indicated that the S value was affected by soil texture, BD and OM content in such a way that S generally increases with decreasing BD and with increasing OM content (Dexter, 2004a). Thus the use of green waste compost led to higher OM content and lower BD, which resulted in increases in S values. Average S values were clearly higher than the critical value (0.035), indicating good soil structural and physical quality.

Aggregate stability

From the second sampling (spring of 2001) onward, there were clear differences in soil Is values between treatments (Fig. 6). In the greenhouse, the Is value of the mineral fertilizer plots did not change compared to the original values, whereas the organic fertilizer plots showed a clear decrease in Is (higher AS) with time. As a result, AS values of organic fertilizer treatments were statistically different from those of the mineral fertilizer treatment and the original plot after the second sampling. The values of the Is in the organic fertilizer plots from the outdoors treatment were lower than those in the mineral fertilizer and original plots, but the differences were smaller than in greenhouse

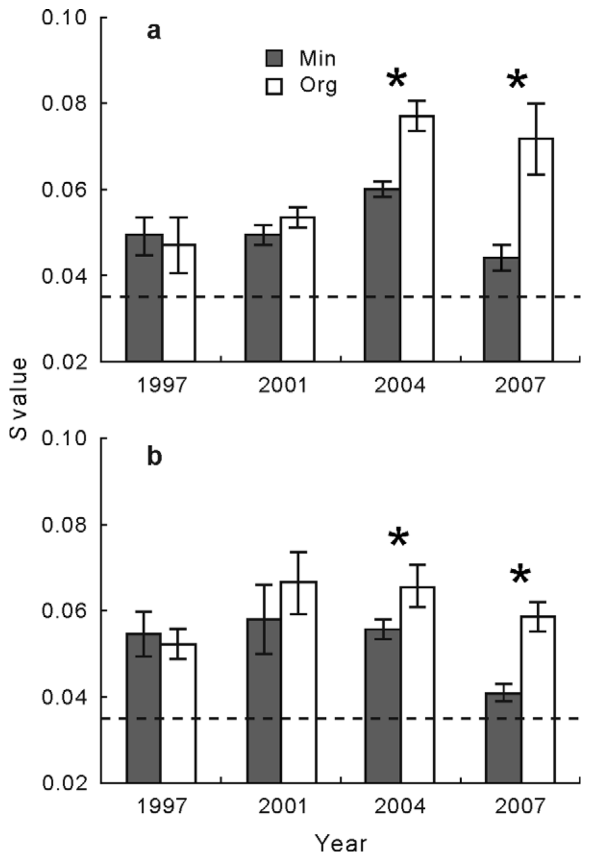

Fig. 5 Mean values of the S parameter of soils in the (a) greenhouse and (b) outdoor plots applied with mineral (Min) and organic (Org) fertilizers at the beginning (1997), after four and seven years (2001 and 2004), and at the end of the study period (2007). *Significant at $P < 0.05$. Error bars represent standard deviations of the means ($n = 12$). The dash line is the critical value (0.035) that indicates favourable soil physical conditions for root growth according to the criteria of Dexter (2004a).

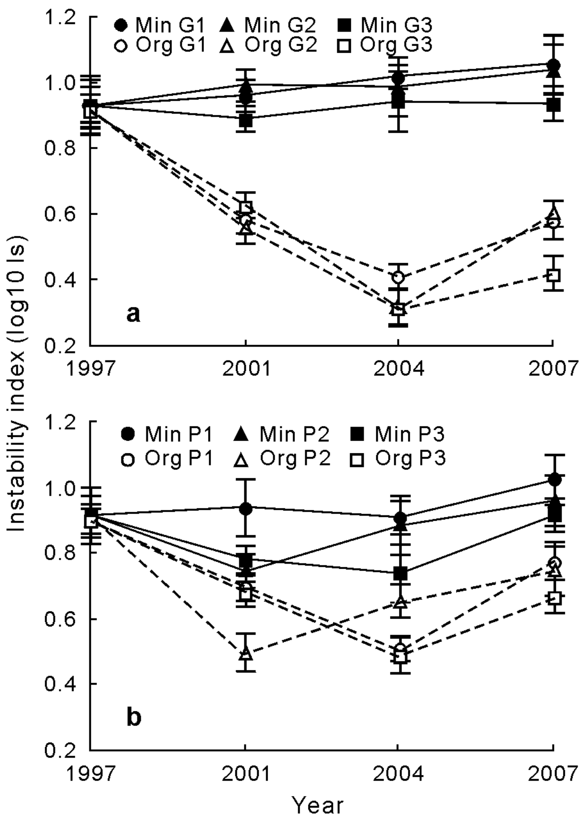

Fig. 6 Instability index (Is) of soils in the (a) greenhouse (G1, G2, G3) and (b) outdoor (P1, P2, P3) plots applied with mineral (Min) and organic (Org) fertilizers at the beginning (1997), after four and seven years (2001 and 2004, respectively), and at the end of the study period (2007). Error bars represent standard deviations of the means ($n = 4$).

plots. In the final samples (year 2007) the differences were significant between fertilizations, mainly in the greenhouse (Fig. 6).

In general, it was observed that the differences in the AS values between the systems of fertilization were higher in the greenhouse. A strong influence from the addition of OM on the stability of aggregates was seen, and this was more evident in the greenhouse.

The organic fertilizer plots also showed higher AS values compared to the mineral fertilizer plots (Fig. 6). Haynes *et al.* (1991) show a clear relationship between the OM and the formation of aggregates. The addition of OM produces an increase in the number and size of soil aggregates (Ekwue, 1992), that is, an increase in AS (Bissonnette *et al.*, 2001; Lu, 2001; Li and Zhang, 2007). The OM and biological activity of soil are intimately related to soil aggregation and soil structure (Haynes and Naidu, 1998). An increase in biological activity due to the addition of OM has a positive effect on the aggregation and macroporosity of the soil. This effect is possibly the principal explanation for our results. In another work carried out in the same plots, the application of OM produced an increase in soil microbial activities (Melero *et al.*, 2006). Pulleman *et al.* (2003) found that in soils under different management conditions over a period of 70 years the stability of the aggregates in soils was significantly greater under organic management than under conventional management, although both were less than the stability in a soil with permanent pasture. Gomez *et al.* (2001) indicated that the Henin instability index (Is) is larger under chisel ploughing than in no tillage management. In other words, the stability of the aggregates decreased as a result of the tillage and agricultural use. In our study, the AS increased in outdoor plots (tillage) and especially in greenhouse plots (no tillage).

Correlations between soil organic matter and soil physical properties

Important changes were observed in the physical properties due to the OM additions. A significant correlation ($P < 0.01$) was observed between the OC and the soil physical properties for all the comparisons (Table III). The BD showed a negative correlation with the OC, which indicated that the OM addition produced a decrease in BD. The BD also showed a negative correlation with the S parameter and a positive correlation with Is, indicating that a decrease in BD improved the soil structural and physical quality. Also there was a negative correlation between the OC and Is, indicating that the stability of the soil increased with addition of OM. Nevertheless AWC showed a significant positive correlation with BD and Is and a negative correlation with OC, but these correlations were weaker in other cases and even did not exist as in the case with the S parameter in outdoor plots.

The high negative correlation which was observed between the OC and the BD (Table III) is due to different factors such as the reduced or no tillage in organic fertilizer plots, and the increase in the labile fraction of the OC that is released through the microbial decomposition of OM and deposited on the soil mineral fraction as a surface coating, yielding soil aggregation. It is particularly interesting to note that the BD was lower in the outdoor plots than in the greenhouse plots (Fig. 2). In the greenhouse, no tillage was carried out and the compost was applied on the surface, whereas the outdoor plots were tilled. Lampurlanés and Cantero-Martínez (2003) reported that no-tillage plots showed the largest bulk densities followed by minimum tillage and subsoil tillage. Tillage initially increases the porosity and the aeration of the soil, stimulating the microbial oxidation of the soil OM. Tillage may have a temporary effect that favours biological activity and increases porosity but the soil can rapidly consolidate (Lampkin, 1998). Blanco-Canqui *et al.* (2009) found that ploughed soils become more easily compacted than untilled soils under the same compactive force and water content.

CONCLUSIONS

The use of vegetal compost and the elimination of synthetic fertilizers resulted in a higher OC content in the greenhouse and outdoor plots. The type and amount of organic amendment used in the present study is suitable to maintain an adequate level of soil OM. The results after ten years of organic fertilization indicate that the use of organic amendment produced a decrease in the BD and an increase in the AS. The additions of OM produced an improvement in the soil structure by increasing porosity, but this did not always produce higher WR. The OC showed a significant negative correlation with BD and Is and a positive one with parameter S, indicating improved soil structural and physical quality. The negative correlation between the OC and AWC indicated the higher influence of the decrease in BD and the higher values of the PWP point in the organic fertilizer plots, but other aspects such as depth of root exploration should be considered for a real comparison of AWC between the systems.

Soil bulk density, S parameter, and AS values were higher in the greenhouse than in the outdoor plots. Therefore differences in management (mainly tillage) exert a significant influence on the evolution of physical properties. This study indicated that the use of vegetal compost without the application of synthetic fertilizers resulted in an increase in the soil OM, depending upon the management system, and different improvements in the physical properties of the soil.

The use of sustainable management techniques such as the use of organic amendments and low or no tillage improved soil physical properties, despite the differences in different management systems (crops, tillage, irrigation systems, *etc.*) that logically affect the results significantly.

TABLE III

Correlation coefficients among organic carbon (OC), bulk density (BD), instability index (Is), available water content (AWC), and Dexter's index (S)

	BD	Is	AWC	S
OC	−0.81**/−0.84**	−0.84**/−0.83**	−0.70**/−0.62**	0.76**/0.64**
BD		0.68**/0.70**	0.44*/0.47*	−0.63**/−0.42*
Is			0.61**/0.57**	−0.66**/−0.58**
AWC				−0.48*/−0.27

*, **Significant at $P < 0.05$ and $P < 0.01$, respectively.

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