

Research Article

Tillage System Affects Soil Organic Carbon Storage and Quality in Central Morocco

R. Moussadek,¹ R. Mrabet,¹ R. Dahan,¹ A. Zouahri,¹ M. El Mourid,² and E. Van Ranst³

¹ *Institut National de la Recherche Agronomique, BP 415, Avenue la Victoire, Rabat, Morocco*

² *International Center for Agricultural Research in the Dry Areas, Menzah IV, 2037 Tunis, Tunisia*

³ *Laboratory of Soil Science, Department of Geology and Soil Science (WE13), Ghent University, Krijgslaan 281/S8, 9000 Gent, Belgium*

Correspondence should be addressed to R. Moussadek; moussa.inra@gmail.com

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Stabilizing or improving soil organic carbon content is essential for sustainable crop production under changing climate conditions. Therefore, soil organic carbon research is gaining momentum in the Mediterranean basin. Our objective is to quantify effects of no tillage (NT) and conventional tillage (CT) on soil organic carbon stock (SOCs) in three soil types (Vertisol, Cambisol, and Luvisol) within Central Morocco. Chemical analyses were used to determine how tillage affected various humic substances. Our results showed that, after 5 years, surface horizon (0–30 cm) SOC stocks varied between tillage systems and with soil type. The SOCs were significantly higher in NT compared to CT (10% more in Vertisol and 8% more in Cambisol), but no significant difference was observed in the Luvisol. Average SOCs within the 0–30 cm depth was 29.35 and 27.36 Mg ha⁻¹ under NT and CT, respectively. The highest SOCs (31.89 Mg ha⁻¹) was found in Vertisols under NT. A comparison of humic substances showed that humic acids and humin were significantly higher under NT compared to CT, but fulvic acid concentrations were significantly lower. These studies confirm that NT does have beneficial effects on SOCs and quality in these soils.

1. Introduction

Management of soil organic matter (SOM) in arable lands has become increasingly important in many areas of the world in order to combat land degradation [1, 2], increase food security [3, 4], reduce C emissions, and/or mitigate climate change [5–7]. In fact, soil carbon cycling and composition are essential components of comprehensive agricultural and ecological impacts and forecasting. Bot and Benites [8] have considered SOM as keys to developing drought-resistant soils (i.e., water conservation, evaporation and erosion control, and soil water infiltration ease) and ensuring sustainable food production (crop productivity, fertilizer use efficiency, reduced pesticide use, and crop ecological intensification) [9, 10].

In Morocco, previous investigations have shown that SOM content in most soils is low (<2%) and the decadal average (from 1987 to 1997) loss of the SOM due to intensive

land use is about 30% [6]. The decline of SOM in cultivated soil of Morocco, due to the tillage intensification, decreased soil quality and increased the risk of soil degradation [11, 12]. In fact, FAO estimated that 71% of Moroccan agricultural soils are degraded and require conservation measures [8].

To deal with this situation, conservation agriculture has been recommended as an alternative strategy to invert the soil degradation spiral in many parts of the world [14–16]. No-tillage systems, which consist of eliminating soil tillage and inversion, maintaining crop residue cover, and ensuring proper crop sequences, have been reported to improve SOM level and ensure carbon accumulation and sequestration in diverse soils from contrasted climate regimes [17]. In the Mediterranean basin, experiences have shown the sustainable use of natural resources through adoption and diffusion of no-tillage systems improves soil quality and enhances crop productivity vis-à-vis climate variability and drought [18, 19]. In other terms, SOM improvement under NT is fundamental

for food system in Mediterranean drylands. In Spain, Álvaro-Fuentes et al. [20] showed that no tillage (NT) increases soil organic carbon (SOC) stock in the soil profile (0–40 cm) compared to CT. Similar results were found in Italy [21], in France [22], and in Morocco [23–25]. It was also found that, under no-tillage systems, dryland soil can play a part in mitigating CO₂ levels [22, 26]. The continuous harvesting of plant materials in conventional tillage system was reported by several authors of decreasing carbon levels in Mediterranean soils and harming its fertility and health [17]. Although most studies reported that no tillage increases SOC storage in the upper soil horizons compared to conventional tillage, other studies reported that SOC content, in deeper horizons, could be similar or even lower under NT than under conventional tillage system [26]. In fact, Franzluebbers [27] reported that SOC stocks depend not only on tillage system, but also on local conditions (soil type and climate).

SOM is a continuum of substances in all stages of decay. Humus is a relatively stable component formed by humic substances, including humic acids, fulvic acids, humatmelanic acids, and humins [28]. Humic and fulvic substances enhance plant growth directly through physiological and nutritional effects [8] but also improve soil health and quality through amelioration of soil's physical, biological, and chemical properties. It is evident to account no-tillage systems as durable management practices; they have to improve and protect simultaneously soil organic matter and its active fraction.

Investigations reported that NT systems affect not only the amount of SOM but also its characteristics [29]. Soil organic matter quality is affected by no tillage either in terms of particulate organic matter [24] or in terms of its composition of humic acids, fulvic acids, and humin [30]. These humic substances are involved in improving soil structural stability and plant growth [31].

In Morocco, the effect of no tillage on SOC content has been largely investigated [32], but studies on the potential storage of SOC under NT, taking into account the effect of soil types, have not been carried out yet. Furthermore, effect of tillage systems on humic substances in semiarid Morocco's environment was not assessed in any previous research. Hence, SOC chemistry remains scarcely studied under tillage systems for the most productive soils in Morocco, as Vertisols. Thus, the objectives of this study are

- (i) to investigate the effect of NT and CT on the SOC stock (SOCs) in three soil types;
- (ii) to quantify the effect of NT and CT on the composition of humic substances in Vertisols.

2. Material and Methods

2.1. Research Sites, Experimental Set-Up, and Crop Management. This study was conducted at the Merchouch plateau (33°34' N, 6°42' W, and 425 m elevation), in Morocco. Its Mediterranean climate is characterised by a mean annual rainfall of 450 mm. Figure 1 shows the monthly time-series (1970–2012) of the average rainfall and temperature and those occurring during the studies period.

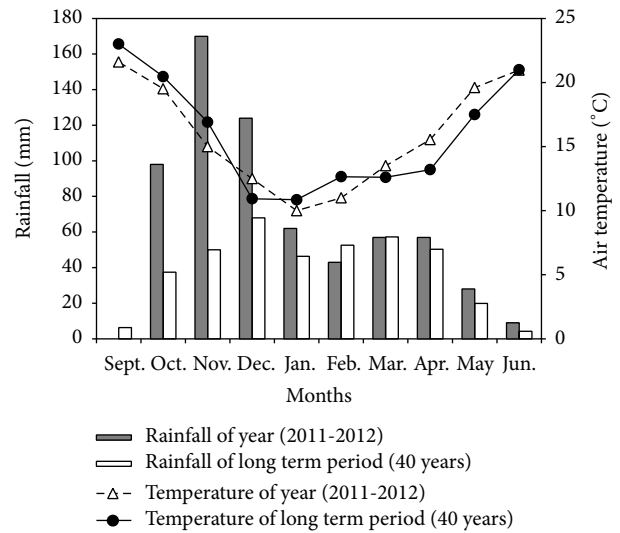


FIGURE 1: Monthly average of rainfall and temperature (2011-2012) at Merchouch compared to monthly values of a long term period (1970–2012).

The experiment was established in autumn 2006 after harvest of wheat. Three sites with different soil types were selected. The soils of different sites were classified as Vertisol at site 1, Cambisol at site 2, and Luvisol at site 3, according to the WRB classification [33]. Table 1 summarises the main soil characteristics of the soils at the 3 sites.

Experimental Set-Up. In the three sites, the trials consist of two tillage systems: no-tillage system (NT) and conventional tillage system (CT), performed on two adjacent plots of 200 m long and 100 m wide each. The CT plots were ploughed, according to farmers' practice in the region, at 30 cm of depth with a "stubble plow" at the end of August each year. For seed-root bed preparation, a pass of a chisel, operated at about 15 cm depth, and two passes with a disc harrow at about 10 cm depth were needed during mid-September. The soil was not disturbed in the plots under NT which were maintained covered with flat and stubble residues at 30% levels. Wheat-lentil rotation was adopted and the crop management was similar in CT and NT treatments. Indeed, winter wheat was sown in mid-November at a 140 kg ha⁻¹ seed rate. In mid-December, lentil was sown at seed rate of 40 kg ha⁻¹. Before sowing, wheat and lentil received a complex fertilizer (14N-28P₂O₅-14K₂O), at a rate of 150 kg ha⁻¹ and 100 kg ha⁻¹, respectively. In addition, wheat received 100 kg ha⁻¹ of urea at the end of February. The control of weeds is based primarily on plowing the soil in CT plot before sowing; while in the NT plot this control was achieved by chemical weeding. In fact, for wheat, flumetsulam herbicide was used at a dose of 50 mL⁻¹ ha before sowing. Before lentil seeding, weeds were treated with 3 l ha⁻¹ of Paraquat.

NT and CT lentils were treated with 1 l ha⁻¹ of fluazifop-P-butyl in early February of each season. For wheat, 50 mL ha⁻¹ of flumetsulam was used in early March of each year to control weeds.

TABLE I: Selected soil characteristics at the different sites (Merchouch, Morocco).

Site/soil	Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Texture class	pH (1.1 H ₂ O)	P ₂ O ₅ (mg/kg)	K ₂ O (mg/kg)	CaCO ₃ total (g/kg)	SOC (g/kg)
Site 1 Vertisol	0–20	49	29.5	21.5	C	7.02	21	234	3.6	12.2
	20–80	52	26.6	21.4	C	7.23	11	133	7.3	11.4
	80–120	53	23.1	23.9	C	7.37	5	139	8.5	9.7
Site 2 Cambisol	0–25	44	37	18	C	7.9	58	237	1.2	11.7
	25–55	41	49	10.0	SiC	7.8	5	133	4.4	11.1
	55–90	38	55	7.4	SiL	7.7	3	108	9.5	5.5
Site 3 Luvisol	0–15	19	36	45	L	7.1	40	259	5.5	7.4
	15–50	25	28	47	L	7.2	14	129	10.5	6.5
	50–100	36	21	43	L	7.4	4	109	10.1	6.2

C: clay; SiC: silty clay; SiL: silty loam; L: loam (following the textural triangle [13]).

After harvest, about 30% of the crop residues were maintained at the surface under no tillage. In fact, to study the effect of residue management on SOC_c under NT system, three 1 m² plots were randomly chosen to harvest in the NT plot in the large plot of 1 ha and the average of residues is calculated per m² and knowing the amount of residues collected, the mechanical combine harvester was set to leave about 30% of the residues in the large NT plot for wheat crop. For lentil, harvest was done manually and 30% of harvested residues were manually dispersed on the surface of NT plot.

In contrast with NT, in CT plots all crop residues were removed from the field according to the conventional farming practices of this region.

2.2. Soil Sampling and Analysis

2.2.1. Soil Organic Carbon Content. In June of 2012, after wheat harvest, disturbed and undisturbed soil samples were taken for determination of the SOC_c content and bulk density, respectively, and at the same time. The soil samples were collected in three different sites at four depths (0–5, 5–10, 10–20, and 20–30 cm) in the NT and CT plots with three replicates per treatment. We selected to use those four depths in this study because studying the effect of soil management on SOC using the entire soil profile can be more complicated and needs a long term SOC monitoring [34].

Immediately after sampling, the disturbed soil samples were dry sieved at 2 mm to remove plant debris. The SOC content was determined indirectly by oxidation of organic carbon following the classical method of Walkley and Black [35]. The organic matter content is estimated by multiplying the SOC content by a correction factor of 1.724. Concerning the soil bulk density (D_b), intact soil cores of 200 cm³ in metal sleeves were collected using a hammer-driven core sampler for the determination of dry bulk density as described by Grossman and Reinsch [36] (Table 1).

2.2.2. Humic Substances. To study the effect of tillage practices on humic substances, soil samples were collected randomly from the Vertisol at 0–20 cm depth in the NT and

CT plots with three replicates per treatment in mid-season (March 2012).

Extraction of humic substances was done using the alkaline solvents method [37]. The fine fraction (<50 μm) was treated with 0.1M sodium pyrophosphate at pH 9.8. From these alkaline substances, separated by centrifugation, the dispersed organomineral colloids were deflocculated with 4% KCl and mixed with insoluble soil residues. The residues were then treated with 0.1N sodium hydroxide at pH 12 using the same protocol [38].

The pyrophosphate and NaOH extracts were mixed. The humic and fulvic acids were separated by acidification to a pH 1.5.

2.2.3. Calculation of Soil Organic Carbon Stock (SOC_s). The stock of soil organic carbon (SOC_s) was expressed using the following equation [39]:

$$\text{SOC}_s = \sum_{i=1}^n D_{b,i} * \text{SOC}_{c,i} * D_i, \quad (1)$$

where SOC_s is the soil organic carbon stock (kg C m²), $D_{b,i}$ is the bulk density (Mg m⁻³) of layer i , $\text{SOC}_{c,i}$ is the proportion of soil organic carbon content (g C g⁻¹) in layer i , and D_i is the layer depth (m).

2.3. Statistical Analysis. The effects of tillage system on the SOC_c, SOC_s, and humic substances were tested in the different soil types using SPSS version 17. Analysis of variance (ANOVA) was used to determine significance of tillage effects in each soil type and t -test (Student's t -test) was applied for comparing treatment means.

3. Results and Discussion

3.1. Soil Organic Carbon Content (SOC_c). Our results showed that SOC_c near the surface (0–10 cm) was significantly higher under NT compared to CT for the three soil types (Figure 2), confirming the results obtained by other authors under semi-arid Mediterranean conditions [20, 32, 40, 41]. The reduction

of SOC_c in conventionally tilled soil could be explained by the excessive removal of biomass after harvest and higher decomposition rate due to increased microbial activity at the soil surface [42, 43]. At 10–20 cm depth, except in Luvisol, SOC_c was significantly higher in NT than CT. However, in the deepest horizon (20–30 cm), no significant difference of SOC_c has been observed between the CT and NT systems. The same findings under similar semiarid Mediterranean conditions were reported by Murillo et al. [44], Moreno et al. [45], and Lozano-García and Parras-Alcántara [46].

Although under semiarid climatic conditions the potential for C sequestration into deep soil horizons is generally restricted, a slight increase of SOC_c in the surface layer is essential to control erosion, water infiltration, and conservation of nutrients and is related with the soil quality [47].

3.2. Soil Organic Carbon Storage (SOCs). Figure 2 shows higher soil D_b under NT than under CT, especially in the top soil (except for Luvisol). Similar results were reported in numerous studies, which showed that bulk density increases in the few years after NT introduction [48–50].

Several authors suggest that this increase in D_b under NT will be reduced with time following increases in soil biological activity [51–53].

Table 2 shows the SOC_c in all layers for both tillage systems under the three soil types. The analysis of variance indicated significant higher SOC_c under NT compared to CT in both 0–5 and 5–10 cm layers under the three soil types. Considering the average SOC_c at 0–30 cm depth, NT had significant higher SOC_c than CT under Vertisol and Cambisol; however no significant difference was observed between the two tillage systems under Luvisol. The SOC_c (0–30 cm) average was 29.35 and 27.36 Mg ha⁻¹ under NT and CT, respectively, with a maximum of 31.89 Mg ha⁻¹ observed in NT under Vertisol (Table 2).

This result indicated that after five years of continuous NT the topsoil (0–30 cm) SOC_c increased by 10% in the Vertisol, 8% in the Cambisol, and 2% in Luvisol compared to CT. This is consistent with the results of Ben Moussa-Machraoui et al. [54] who observed an improvement of 12% of SOC_c in a Tunisian Cambisol after 4 years of NT compared to CT.

Similarly, [18] observed a significant increase in SOC_c of a Vertisol after 4 years of NT compared to CT in semiarid Morocco. In a long term study, [24] reported that SOC_c in Vertisol was 13.6% higher under NT than under CT after 11 years under drier conditions compared to our study area.

In contrast, we did not observe a significant effect of NT on (0–30 cm) SOC_c in the Luvisol, compared to CT. This is in agreement with results reported by Virto et al. [55] and Thomas et al. [56] in a Luvisol under semiarid climate. The higher C sequestration potential under NT of Vertisols and Cambisols versus Luvisols can be explained by differences in their texture. Several researchers have shown that fine-textured soils have a greater potential to sequester carbon than coarse-textured soils [5, 57, 58]. In fact, SOC_c is higher in soils with fine texture due to the stabilizing properties that clay has on organic matter which could be trapped in the very small spaces between clay particles reducing the accessibility

of the microorganisms and therefore slowing SOC decomposition. This is the mediated aggregation process by carbon accumulation as explained by Six et al. [59]. Many authors reported that soils with high clay content tend to have higher SOC than soils with low clay content under similar land use and climate conditions [27, 60].

In this sense, [61] described Vertisols as “active” soils in NT due to the high amount of clay which could improve soil organic carbon content.

Concerning the organic carbon storage, SOC_c varied between 31.9 Mg·ha⁻¹ and 25.8 Mg·ha⁻¹ under NT, while, in tilled treatments, SOC_c ranged between 28.8 Mg·ha⁻¹ and 24.8 Mg·ha⁻¹. These values were lower than those observed by Fernández-Ugalde et al. [62] who found, in silty clay soil, a SOC_c at 0–30 cm of 50.9 Mg·ha⁻¹ after 7 years of no tillage, which was significantly higher than the 44.1 Mg·ha⁻¹ under CT under wheat-barley cropping system in semiarid area in Spain. In the same Mediterranean climate, Hernanz et al. [63] found, after 11 years under NT, a SOC_c of 37 Mg·ha⁻¹ which was higher than 33.5 Mg·ha⁻¹ under CT, using a wheat-vetch (*Vectoria sativa* L.) rotation in silty soil. The lower SOC_c values we observed can be explained by the fact that more time is needed before achieving the peak sequestration rate under NT. According to West and Post [64], this peak could be reached within 5–10 years after the introduction of NT.

3.3. Humic Substances. According to Figure 3, the organic matter under NT was composed of significantly higher amounts of humic acids (HA) and humin (HU) and lower amounts of fulvic acids (FA) compared to CT in Vertisol. This is consistent with results obtained by Szajdak et al. [65]. The relative decrease in FA under NT compared to CT was probably due to the humification process which was favored by residue management under NT and resulted in a significant increase of the most stable fraction (HA and HU) [66].

Blanco-Canqui and Lal [67] reported that the increases of the humic acids are particularly involved in aggregate stabilization more than fulvic acid. According to Piccolo et al. [68], additional HA serve to bond particles together and can be adsorbed onto clay particles by polyvalent cations, making them especially effective in reducing clay dispersion, improving soil water content, and reducing soil erosion [69]. In fact, in the studied Vertisol, positive effects of NT on aggregate stability and soil water content have been reported in a previous study by Moussadek et al. [25].

4. Conclusions

The introduction of no tillage (NT) in wheat-based systems of Central Morocco could be an alternative for improving soil quality. After five years of NT, a significant increase in soil organic carbon (SOC) was found compared to CT for two major soils (Vertisol and Cambisol). SOC stock increased from 2% to 10%, depending on the soil type. Indeed, Vertisols or similar clay soils in general are able to store more SOC under NT along the profile than coarse textured soil. This accumulation of organic carbon resulted in increased levels

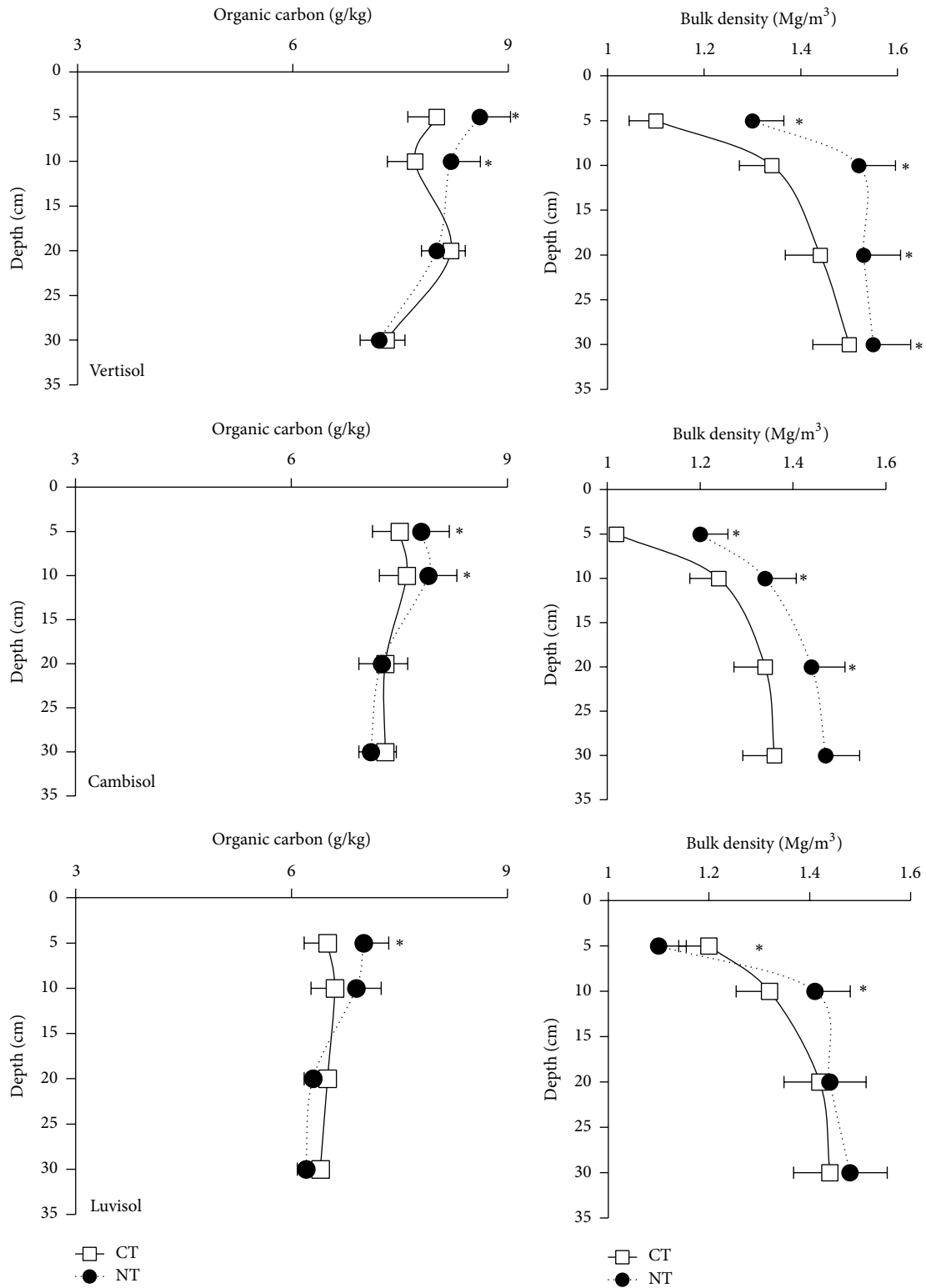


FIGURE 2: Soil organic carbon content (SOCc) and bulk density (D_b) in three soil types after 5 years under NT and CT. At each depth, (*) means the presence of significant differences between treatments (LSD test, $P < 0.05$). The error bar represents one standard error.

TABLE 2: Soil organic carbon storage (SOCs) ($\text{Mg}\cdot\text{ha}^{-1}$) in three sites under no tillage (NT) and conventional tillage (CT) in Merchouch, Morocco.

Depth (cm)	Vertisol		Cambisol		Luvisol		Average	
	NT	CT	NT	CT	NT	CT	NT	CT
0–5	5.39 ^a	4.14 ^b	4.91 ^a	4.07 ^b	4.02 ^a	3.31 ^b	4.77 ^a	3.84 ^b
5–10	5.83 ^a	4.62 ^b	5.70 ^a	4.63 ^b	5.09 ^a	4.69 ^b	5.54 ^a	4.65 ^b
10–20	11.32 ^a	10.77 ^b	10.35 ^a	9.81 ^b	8.54 ^a	8.61 ^a	10.07 ^a	9.73 ^a
20–30	9.34 ^a	9.26 ^a	9.80 ^a	9.98 ^a	7.77 ^a	8.18 ^a	8.97 ^a	9.14 ^a
Total (0–30 cm)	31.89 ^a	28.79 ^b	30.76 ^a	28.49 ^b	25.41 ^a	24.79 ^a	29.35 ^a	27.35 ^b

^{a,b} For the same soil and the same depth, treatments with the same letter are not significantly different; Student's *t*-test ($P < 0.05$).

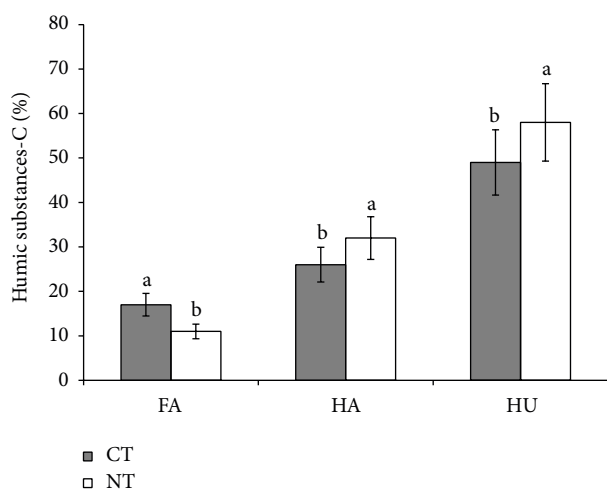


FIGURE 3: Humic substances in Vertisol under NT and CT (FA: fulvic acid; HA: humic acid; HU: humin), for each of the substances (treatments with the same letter are not significantly different (Student's *t*-test with $P < 0.05$)).

of humic acids and humin in Vertisol under NT compared to CT. The obtained result shows that NT can contribute to the improvement of soil quality in semiarid Mediterranean conditions.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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