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RESEARCH ARTICLE

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Tillage effects on soil properties, crop responses and root density of sweet pepper (*Capsicum annuum*)

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Abstract

Aim of study: Soil compaction causes an increase in bulk density, resistance to penetration, low diffusion of oxygen and water in the soil. Tillage is one of the techniques to alleviate compaction. The objective of this work was to evaluate the effects of tillage on sweet pepper grown in greenhouse soil.

Area of study: The experimental work was conducted in a plastic greenhouse at the Experimental Station of the University of Almería (SE Spain).

Material and methods: The soil was ploughed with a single pass with ripper to 15 cm depth and with rotavator to 10 cm depth. The control treatment was soil untilled. Crop dry matter production and root length growth and density of sweet pepper were evaluated, in addition to soil characteristics such as bulk density, resistance to penetration and soil matric potential.

Main results: Tillage reduced soil bulk density from 1.70 to 1.60 kg L^{-1} in the 10-40 cm of soil depth. There was a notable reduction in irrigation (12%), total N applied (13%), drainage (91%) and N leaching (95%) in the tillage treatment. However, tillage did not improve significantly crop dry matter production and yield. The absence of tillage effect is possible due to a slight reduction in the bulk density of the soil.

Research highlights: The tillage treatment produced a notable reduction in irrigation, total N applied, drainage and N leaching when compared to the control.

Additional key words: bulk density; drainage; soil compaction; soil layer; soil matric potential; vegetable crops.

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Introduction

Soil structure is one of the main factors affecting crop growth over the long term (Passioura, 1991). Good soil structure consists of soil aggregation associated with high porosity, rapid infiltration rates, water retention capacity and increased air circulation which all facilitate root penetration and proliferation (Primavesi, 1982). A major problem of modern agriculture is the loss of soil aggregation, with compaction being one of the most important causes (Hamza & Anderson, 2005; Batey, 2009). Compaction alters the overall structure of soil pores, reduces pore number and size, and increases soil bulk density and resistance to soil penetration (Iler & Stevenson, 1991; Abu-Hamdeh, 2003).The effect of soil compaction on crop growth depends on soil texture. In general, soil bulk density values that limit root growth are 1.40–1.45 kg L^{-1} in silty to clay textured soil, and 1.65–1.75 kg L^{-1} in sandy soils (Daddow & Warrington, 1983).

The most frequent causes of soil compaction are use of heavy machinery, intensive cultivation, no crop rotation, and inadequate soil management (Hamza & Anderson, 2005;

Batey, 2009). Soil compaction is accentuated in soils with low organic matter content and in soils with high moisture content (Hamza & Anderson, 2005). Organic matter loss can cause soil disaggregation, increasing susceptibility to compaction (Cochrane & Aylmore, 1994).

Soil tillage is a management practice that can alleviate soil compaction in diverse agricultural systems (Abu-Hamdeh, 2003; Quincke *et al.*, 2007; Wortmann *et al.*, 2008). Erbach *et al.* (1992) reported that different forms of tillage reduced differentially soil bulk density and resistance to penetration within the depth of tilled soil. The most effective tillage practices increase availability of soil water to crops due to increased infiltration (Lampurlanés *et al.*, 2001). In crop rotations of wheat and maize, deep tillage increased yield due to a reduction of soil compaction and increased soil water holding capacity (Mu *et al.*, 2016). Soil management practices that facilitate deep rooting are likely to improve the efficient use of N and water, thereby decreasing the likelihood of nitrate (NO_3^-) leaching (Thorup-Kristensen, 2011).

The compaction processes in soil-grown crops in greenhouse have become widespread worldwide. Indeed, higher soil bulk density values have been reported for greenhouse soils than in bare soils (Liang *et al.*, 2013). In recent years, mechanization in greenhouse crops has increased notably, which resulted in an increase in soil compaction (Erdem *et al.*, 2006). This has led to increased soil bulk density, with values above 1.60 kg L^{-1}, whereas root growth is thought to be restricted above 1.75 kg L^{-1} (Primavesi, 1982). Serious compaction and soil degradation have been detected in greenhouse crops due to continuous cultivation, such as in cucumber crops (Liang *et al.*, 2013).

In the area of Almería, in south eastern Spain, the system of cultivation in "enarenado" soil is used, which consists of covering the soil with a layer of siliceous sand that maintains humidity (Valera *et al.*, 2014). A drip irrigation system is used with fertigation by tapes, in order to apply the dissolved fertilizers in the irrigation water, and the soil is kept constantly humid (Thompson *et al.*, 2007a). Within greenhouses, most cultural practices such as transplanting, pruning, harvesting, and the application of plant protection products are carried out manually by farm workers (Valera *et al.*, 2014; Padilla *et al.*, 2017). Due to the presence of a sand mulch, tillage is hardly carried out, since the sand mulch layer must be removed prior to tillage and be replaced (Valera *et al.*, 2014). The low frequency of tillage accentuates soil compaction processes in SE vegetable crops (Castilla, 1986; Martinez, 1987; Padilla *et al.*, 2017).

The objective of this work was to assess the effects of tillage on soil properties, crop responses and root length growth and density of sweet pepper (*Capsicum annuum* L.) grown in soil in a greenhouse in SE Spain. We measured soil properties (bulk density, resistance to penetration, soil matric potential), crop responses (dry matter production, crop yield, nitrogen N uptake) and rooting pattern (root length density, relative root length distribution, root observation through minirhizotron tubes).

Material and methods

Experimental details

The work was carried out in a plastic greenhouse located at the Experimental Farm of the University of Almería (Almería, Spain, 36° 51' N, 2° 16' W; 92 m elevation). The area of the greenhouse dedicated to the crop was approximately 1,300 m^2. The greenhouse was similar to commercial greenhouses of the Almería region.

Two sweet pepper (cv. Melchor) cropping cycles were grown in soil with a summer-winter cycle, from 18 July 2016 to 24 March 2017 (248 days from transplant to end; hereafter the 2016-17 crop), and from 21 July 2017 to 20 February 2018 (214 days from transplant to end; hereafter the 2017-18 crop).

The soil was an artificial layered "enarenado" soil, which is typical of the region (Valera-Martínez *et al.*, 2016). The "enarenado" soil consists of a 30 cm layer of silty clay loam soil, imported from a quarry, placed over the original sandy loam soil and a 10 cm layer of course river sand placed on the imported silty clay loam soil as a mulch (Padilla *et al.*, 2017).

There were eight plots of 6 × 6 m, with four plots (*i.e.*, replications) per treatment in a fully randomized block design. Polyethylene film sheets buried to 30 cm depth in the borders of the plots prevented water movement between plots. Five-week-old seedlings were planted 6-8 cm from each dripper; the plant density was 2 plants/m^2.

Drip irrigation and fertigation were used. Drippers with a flow rate of 3 L h^{-1} were installed every 50 cm in drip lines, arranged in paired lines with an 80 cm separation. There was a 120 cm spacing between the paired driplines. There were 2 emitters/m^2. Fertigation with complete nutrient solutions, applying all macro and micronutrients commenced at 9 and 10 days after transplant for the 2016-17 and 2017-18 crops, respectively. The N concentrations applied was the same for the two cycles, 9.7 mmol L^{-1}. All cultural practices were consistent with local crop management.

Climatic conditions were recorded inside the greenhouse throughout both crops. Data were stored in a datalogger.

Tillage treatments

There was a tillage treatment and a control with no tillage (*i.e.*, conventional soil management). For the tillage treatment, the gravel mulch was removed, and the soil was ploughed with a single pass with ripper to 15 cm depth, followed by a single pass with rotavator to 10 cm depth. A small tractor pulled the tillage implements. Following cultivation, the gravel was replaced on the surface of the cultivated soil and was evenly spread to form a 10 cm thick mulch layer. Tillage was conducted at the end of June 2016, before the commencement of the 2016-17 crop. No tillage was conducted before the 2017-18 crop. There were four replicated plots of the tillage and no tillage treatments.

In both treatments, irrigation volumes and frequency were modified to maintain soil matric potential between -15 and -25 kPa. Tensiometers (Irrometer Co., Riverside, CA, USA) were installed at 25 cm depth (relative to the surface of the gravel mulch layer) in each plot to measure soil matric potential. The range of -15 to -25 kPa range avoided crop water stress (Thompson *et al.*, 2007b). The intended applied N concentration of fertigation of both treatments was of 10 mmol L^{-1}; 92% of applied mineral N was in the form of NO_3^-, the rest as ammonium (NH_4^+)

Irrigation volumes were measured with water meters. Nutrient solution samples were collected in both treatments, two times per week, to determine the NO_3^- and NH_4^+ concentrations (SAN++, Skalar Analytical B.V., Breda, The Netherlands). Drainage was collected from free-draining lysimeters (Gallardo *et al.*, 2014). Drainage was collected from free-draining lysimeters, the soil of the lysimeter reproduced the "enarenado" soil, their detailed description is in Gallardo *et al.* (2020).

Soil parameters measurements

Soil bulk density was determined one month after soil cultivation, on 27 July 2016. Soil coring rings (5.3 cm internal diameter, 4 cm wall height, Eijkelkamp Soil and Water, Giesbeek, The Netherlands) were used for determination at 15.5-19.5 and 30.5-34.5 cm soil depths. All soil depth values are relative to the surface of gravel mulch. One determination was conducted in each replicated plot. Each sample was taken 8 cm from a plant perpendicular to the line of plants.

Soil penetration resistance (kPa) was measured with a compaction meter (FieldScout SC 900, Spectrum Technologies, Inc., Aurora, IL, USA). Measurements were recorded automatically in a data logger for every 2.5 cm of soil depth, from 10 to 25 cm. The sampling point was at 8 cm from the plant perpendicular to the line of plants. In each of the two pepper crops, measurements were conducted at the beginning and at the end of the crop.

Mineral N (NO_3^-–N and NH_4^+–N) content of the soil was determined immediately before and at the end of each of the two crops. Sampling in each plot was located at 5 and 60 cm from the plant perpendicular to the line of plants. Soil mineral N was calculated as: 0.65 × position 5 cm + 0.35 × position 60 cm (Soto *et al.*, 2015). The soil was sampled in each position to a depth of 70 cm in three depth intervals (10–30, 30–50, 50–70 cm). Soil mineral N content was determined following extraction with potassium chloride (40 g moist soil: 200 mL 2 mol L^{-1} KCl). NO_3^- and NH_4^+ concentrations in the extracts were determined with an automatic continuous segmented flow analyser (Model SAN++, Skalar Analytical B.V., Breda, The Netherlands).

Crop dry matter production and yield

Crop dry matter production and yield was determined from eight plants, in an area of 4 m^2, in each plot. Plants were removed at ground level and the fresh weight material of all leaf, stem and fruit was determined. Dry weight was obtained after oven-drying subsamples at 65 °C. Mass of pruned material was determined as described above. Subsamples of leaf, stem and fruit were individually ground and sequentially in a knife mill and ball mill. Total N content (%) was determined (Rapid N, Elementar Analysensysteme GmbH, Hanau, Germany). The mass of N in leaf, stem and fruit was calculated from %N and mass of dry matter of that component. Crop N uptake (kg ha^{-1}) was the sum of N in leaf, stem and fruit.

Root analyses

Towards the end of both crops, on 31 January 2017 and on 15 February 2018, soil cores were taken at 10 cm from the plant (P1) and at 30 cm from the plant (P2), perpendicular to the line of plants. In each position, the gravel mulch layer and 10-20, 20-30 and 30-40 cm depth layers were sampled; depth is expressed relative to the surface of the gravel mulch. A soil auger of 4.5 cm internal diameter was used for the gravel mulch layer and an auger of 3 cm internal diameter for the 10-20, 20-30 and 30-40 cm soil layers. Two replicate cores per sampling position were collected in each of four replicated plots of each of the two tillage treatments.

Roots of each gravel and soil sample were washed and were dyed with neutral red. Washed roots were scanned (Epson Perfection V800, Seiko Epson Corporation, Nagano, Japan) at 400 dpi in grey scale. The WinRHIZO Reg 2016 software (Regents Instruments Inc., Quebec, Canada) was used to measure root length in each sample. Relative root length distribution in each soil layer, relative to the whole soil profile sampled, was calculated as the percentage of root length in each soil layer divided by the total root length in the whole soil profile.

Transparent minirhizotron tubes were installed to non-destructively monitor root dynamics of sweet pepper throughout the 2017-18 crop. Installation of tubes occurred one year before, in July 2016, to allow for soil stabilization. The minirhizotron tubes were installed vertically to a depth of 48 cm from the surface of the gravel mulch, and at a distance of 10 cm from the plant in the direction of the line of plants. The tubes were of polymethyl methacrylate and were 60 cm long with 6.4 cm internal diameter. PVC caps were glued in the bottom of the tubes. The part of the tube that protruded above the gravel mulch layer was wrapped in aluminium tape to prevent light penetration. Two images (22 × 19 cm, 300 dpi) were taken per tube, the first one from the surface of the gravel mulch to a depth of 22 cm (0-22 cm, hereafter), and the second one from 22 to 44 cm depth (22-44 cm, hereafter). The 0-22 cm image comprised the 10 cm of the gravel mulch and the first 12 cm of the imported soil; the 22-44 cm image comprised the rest of imported soil and some of the original soil. Tube images were scanned (CI-600 Root Scanner, CID Inc., Camas, WA, USA) at 300 dpi and roots were digitized and analysed for root length per square meter of soil using the WinRHIZO Tron 2019 software (Regents Instruments Inc.). During the 207-2018 crop, tube images were taken every 43 days, on average; however, during the first 90 days of the crop, it was every 26 days on average.

Data analysis

In each of the two crops, differences in measured parameters between the tillage and no tillage treatments were tested by factorial analysis of variance (ANOVA) and pairwise LSD tests. Significant differences were established at $p<0.05$. Factors of ANOVA included block, tillage treatment and soil layer. Root length dynamics of minirhizotron tubes were evaluated by repeated-measure analysis of variance (RM-ANOVA). The ANOVA analysis were performed with the STATISTICA 13 software (TIBCO Software Inc., Palo Alto, CA, USA).

Results

Soil parameters measurements

Soil bulk density was slightly reduced in the tillage treatment (averaged value of 1.60±0.03 kg L^{-1}) when compared to the no tillage treatment (averaged value of 1.70±0.03 kg L^{-1}). The relative reductions in the tillage treatment were of 7.3 and 5.5%, for the 15.5-19.5 cm and30.5-34.5 cm depth soil layers, respectively.

In both crops, soil penetration resistance (kPa) was reduced in the tillage treatment throughout the depth of soil that was measured (*i.e.*, 15.5-19.5-25 cm), both at transplanting and at the end of the crop (Fig. 1). The reduction of penetration resistance in the tillage treatment was larger in the first crop (2016-2017), being 52% at transplanting and 36% at the end of the crop, considering the 15.5-19.5 cm depth. Soil penetration resistance was also reduced in the tillage treatment during the second crop (Fig. 1).

Cropping details

Climatic conditions of both crops were very similar in terms of air temperature, relative air humidity and the integral of solar radiation. There were notable differences in soil matric potential between crops, with the 2016-17 crop having less negative soil matric potential values (*i.e.*, wetter soils) than the 2017-18 crop (Fig. 2). Soil matric potential in the tillage and no tillage treatments was very similar (Fig. 2); the averaged soil matric potential of the no tillage treatment was only 2.6 and 1.6 kPa more negative (*i.e.*, drier) than that of the tillage treatment, for the 2016-17 and 2017-18 crops, respectively.

Total N applied and irrigation were notably reduced in the tillage treatment in both crops (Table 1). The averaged reductions in the tillage treatment were of 12% for irrigation, and 12.5% for total N applied (Table 1; Fig. 3). There were large reductions in drainage and N leaching in the tillage treatments, being 91% for drainage, and 95% for N leaching (Table 1; Fig. 3).

Irrigation and the amount of N applied through fertigation was lower in the 2017-18 crop (Table 1; Fig. 4). Drainage and N leaching was lower in the 2017-18 crop (Table 1; Fig. 4). Regarding the comparison between tillage treatments, N concentration in nutrient solution of fertigation (Table 1) in the tillage and no tillage treatments were maintained in very similar values for both treatments

Crop dry matter and yield

There was no significant effect of tillage on crop dry matter and yield in any of the two crops (Table 2). Crop N uptake was significantly higher (13%) in the tillage treatment compared to the no tillage treatment in the 2016-17 crop; there were no significant differences in the 2017-18 crop.

Root analyses

Tillage had a significant effect on root length density in the first crop (2016-17 crop) but not in the second crop (2017-18 crop) (Table 3). The effect of tillage on root length density in the 2016-17 crop was dependent on the sampling position as revealed by the significant Tillage × Position interaction but was independent of layer (Table 3). Tillage significantly increased root length density in the P2 sampling position (*i.e.*, at 30 cm from the plant),

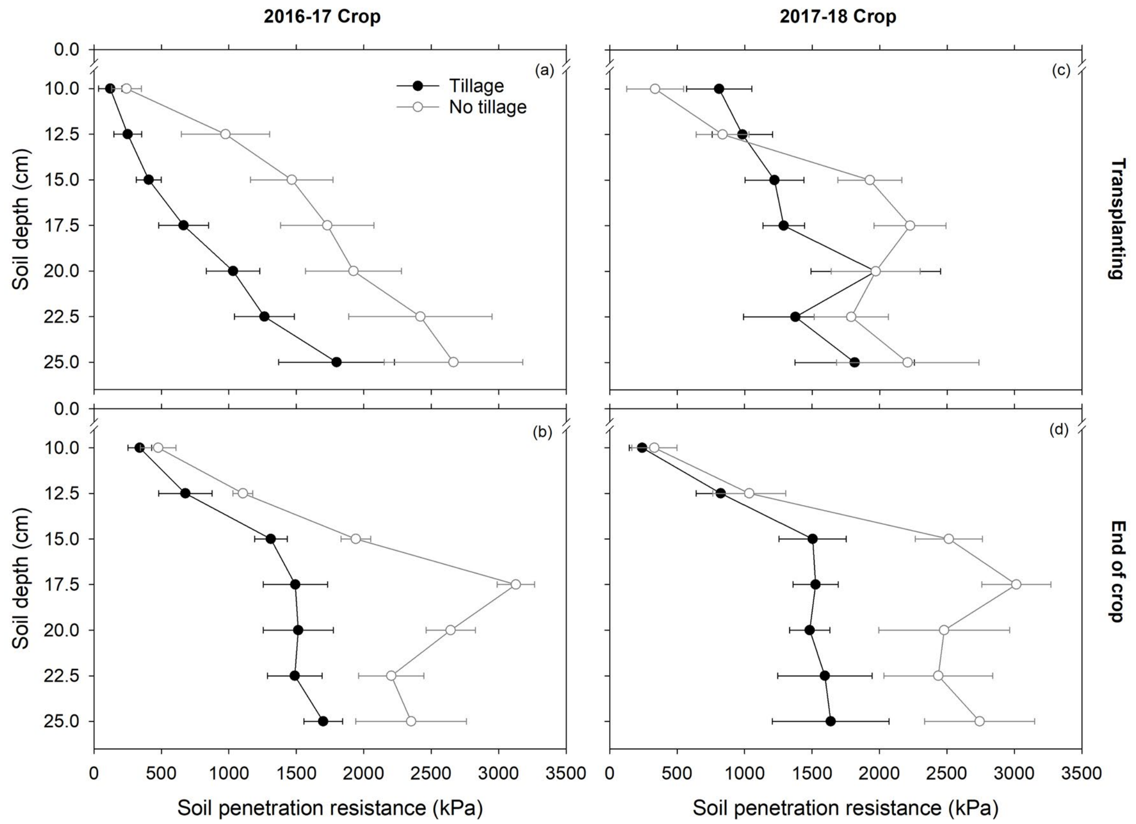

Figure 1. Soil penetration resistance in the two treatments (tillage and no tillage), after transplanting (a and c) and at the end of the crop (b and d), of two sweet pepper crops grown in soil in a greenhouse. Panels (a) and (b) show data of the 2016-17 crop, and panels (c) and (d) show data of the 2017-18 crop. Values are means ± SE.

but not in the P1 sampling position (at 10 cm from the plant), regardless of the soil layer (Fig. 4).

Tillage did not have significant effects on relative root length distribution, in either crop (Table 3). There was a marginal Tillage × Layer interaction in the 2016-17 crop (p=0.069) whereby tillage decreased root length in the gravel mulch layer and increased root length in the rest of soil layers (Fig. 5).

Tillage had no significant effect on root length dynamics observed throughout the crop in minirhizotron images in the 2017-18 crop (Table 4; Fig. 6). Root length growth rate in the 0-22 cm soil layer was estimated at

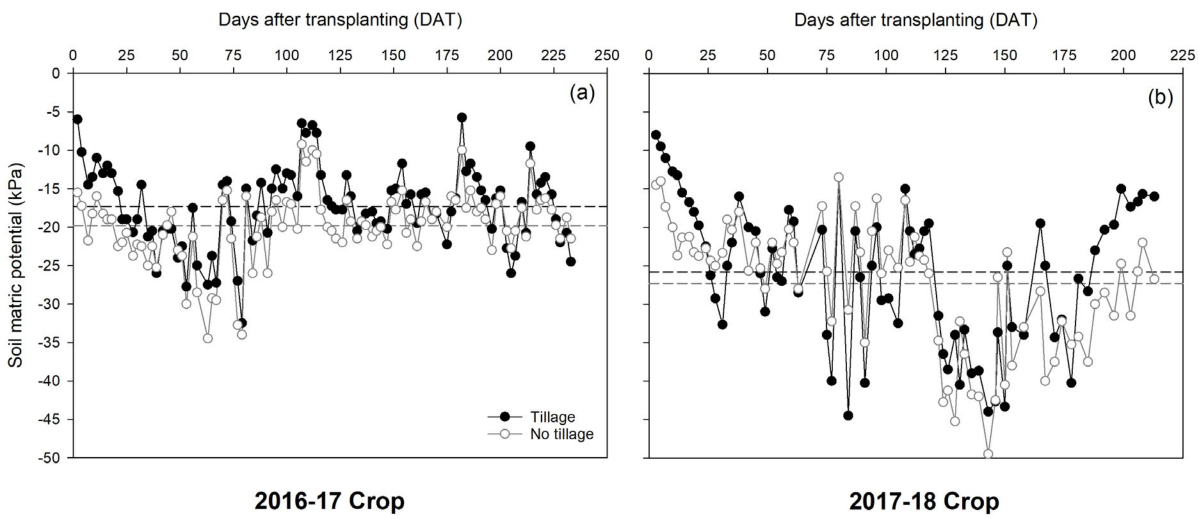

Figure 2. Daily soil matric potential in the two treatments (tillage and no tillage) during two sweet pepper crops grown in soil in a greenhouse. Panel (a) shows data of the 2016-17 crop, and panel (b) shows data of the 2017-18 crop. Values are means of four replications per treatment. Horizontal dotted lines represent the average over the entire crop cycle.

Table 1. Crop details and significance of t-tests between the two treatments (tillage and no tillage), of two sweet pepper cropping cycles conducted in soil in a greenhouse. Within each crop and variable, different lower-case letters indicate significant differences between treatments at p<0.05. Values are means ± SE.

Crops	Treatment	N initial‡ (kg N ha^{-1})	[N] nutrient solution (mmol L^{-1})	Irrigation (mm)	N applied (kg N ha^{-1})	Drainage (mm)	N leached (kg N ha^{-1})	N residual‡ (kg N ha^{-1})
2016-17	Tillage	84±12a	9.7	413	538	14±5a	27±11a	192±42a
	No tillage	54±4a	9.6	502	647	112±14b	72±8b	312±59a
2017-18	Tillage	49±8a	9.7	383	519	3±0a	0±0a	113±18a
	No tillage	36±9b	9.9	407	561	60±1b	18±3b	169±15b

‡10-70 cm soil depth

96±6 m m^{-2} year^{-1} in the tillage treatment and 104±16 m m^{-2} year-1 in the no tillage treatment (p=0.680). In the 22-44 cm soil layer, root length growth rate was estimated at 52±7 m m^{-2} year^{-1} in the tillage treatment and 73±14 m m^{-2} year^{-1} in the no tillage treatment (p=0.314).

Discussion

Several studies have shown reduced soil compaction after tillage in greenhouse-grown vegetable crops, such as Erdem *et al.* (2006) and Padilla *et al.* (2017) in sweet pepper, and Castilla (1986) in tomato. In the present study, it is possible that reduction of soil compaction due to tillage was less than expected because of movement of machinery during tillage, which is a cause of soil compaction, the effect of which is accentuated in moist soils (Batey, 2009). In the confined space of this experimental greenhouse, manoeuvring the tractor and tractor-mounted equipment was not straightforward. It is also possible that ploughing with a single pass with ripper to 15 cm depth, followed by a single pass with rotavator to 10 cm depth, were not the most adequate procedures.

There was a notable reduction in soil penetration resistance in the tillage treatment. This effect was greatest at the beginning of the first crop (2016-17 crop) and was progressively diluted until the end of the second crop (2017-18 crop). The constant passage of personnel for cultural practices and manually pushed carts may have increased soil penetration resistance during the first crop, in addition to a soil that is constantly kept close to field capacity (Padilla *et al.*, 2017). These conditions of high soil moisture may have causes the soil compaction processes to be accelerated (García *et al.*, 2016). This is coincident with Erdem *et al.* (2006) in a sweet pepper crop grown in a greenhouse: soil penetration resistance increased during the first 40 days of the cycle due to irrigation management and mechanical weed control.

This study succeeded in maintaining very similar soil water status in the root zone in both treatments. The averaged soil matric potential recorded in the two treatments, during the two crops, was -22.6 kPa; this value is sufficient enough to prevent water stress in sweet pepper as the leaf water potential threshold values for water stress, for sweet pepper in greenhouse-grown crops, was determined at -58 kPa (Thompson *et al.*, 2007b). Similar soil matric potentials in the tillage and no tillage treatments were achieved by adjusting irrigation volumes to maintain the soil matric potential, at 25 cm depth relative to the gravel mulch, within the range of -15 and -25 kPa. As a result of this irrigation management, irrigation volume and consequently total N applied through fertigation was reduced 12 and 12.5% in the tillage treatment, respectively. It is possible that tillage increased the rate of water infiltration into the soil, which would result in increased soil water retention (Hamza & Anderson, 2005), which is consistent with results of Wang *et al.* (2015) where increased soil water content was found in response to tillage in greenhouse-grown pepper crops. On the contrary, in the treatment without tillage, the irrigation volume had to be greater to maintain the same soil matric potential (Quincke *et al.*, 2007).

The present study found that tillage notably reduced drainage (91%) and consequently N leaching (95%) compared to the no tillage treatment, suggesting that tillage increased soil water infiltration. There is consensus in literature that reduced soil bulk density after tillage generally increases infiltration rates and nutrient leaching losses (Hamblin, 1986; Passioura, 1991; Hamza & Anderson, 2005; Quincke *et al.*, 2007). In the treatment with tillage, the irrigation volume was also lower, in this way it is possible that the washing of N was also lower (Thompson *et al.*, 2007b). In contrast, Pareja-Sánchez *et al.* (2017) reported that soil water infiltration was greatly reduced under tillage compared to no tillage in maize crops. The underlying mechanism seemed to be in the destruction of soil structure and formation of a tillage pan, resulting in lower soil water infiltration rates (Pareja-Sánchez *et al.*, 2017).

Tillage had no significant effects on crop dry matter production and crop yield in either crop, but crop N uptake was increased during the first crop (2016-17 crop).

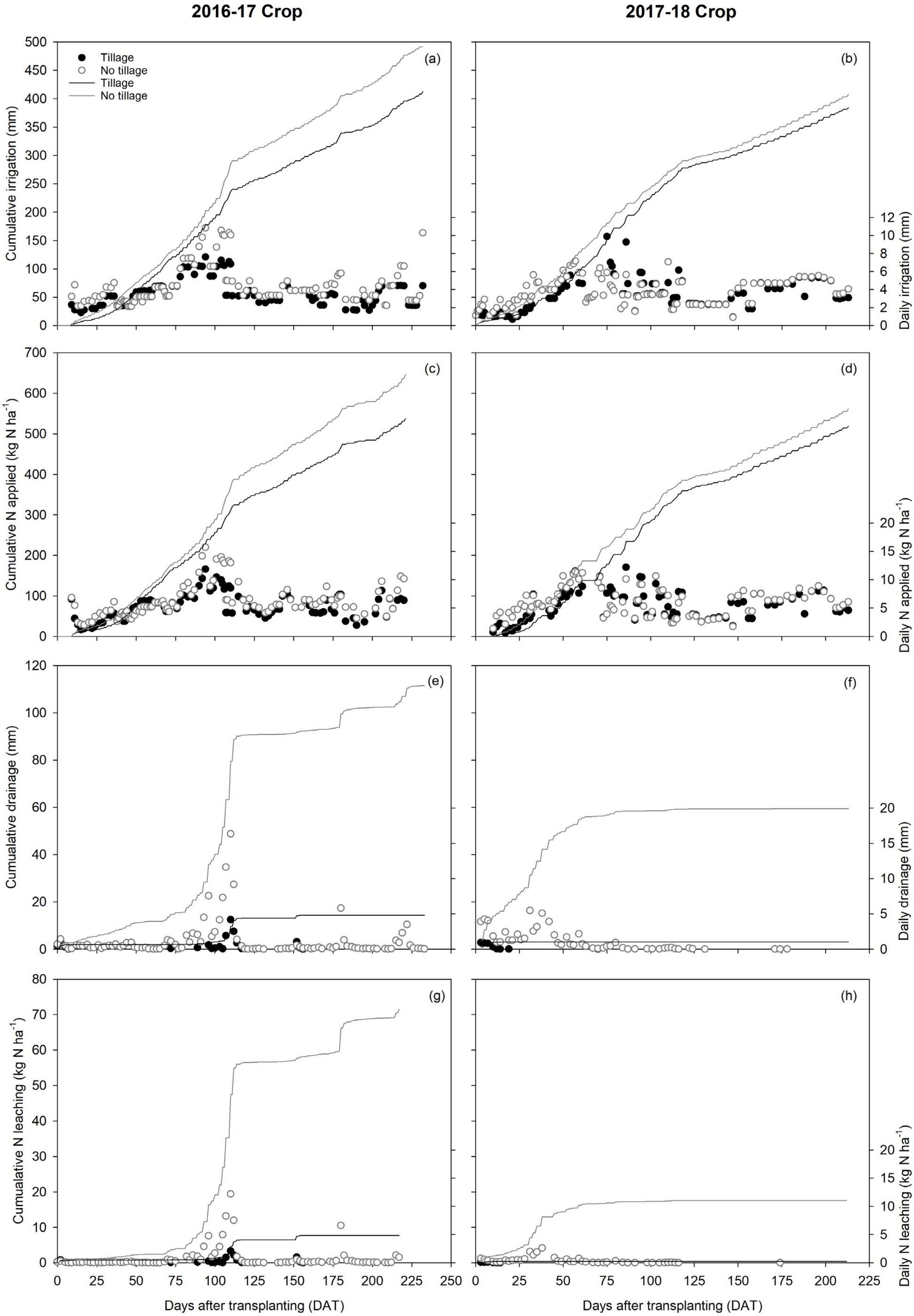

Figure 3. Irrigation, N applied, drainage and N leaching in the two treatments (tillage and no tillage) during two sweet pepper crops grown in soil in a greenhouse. Lines show cumulative values (left axis) and dots show daily values (right axis).

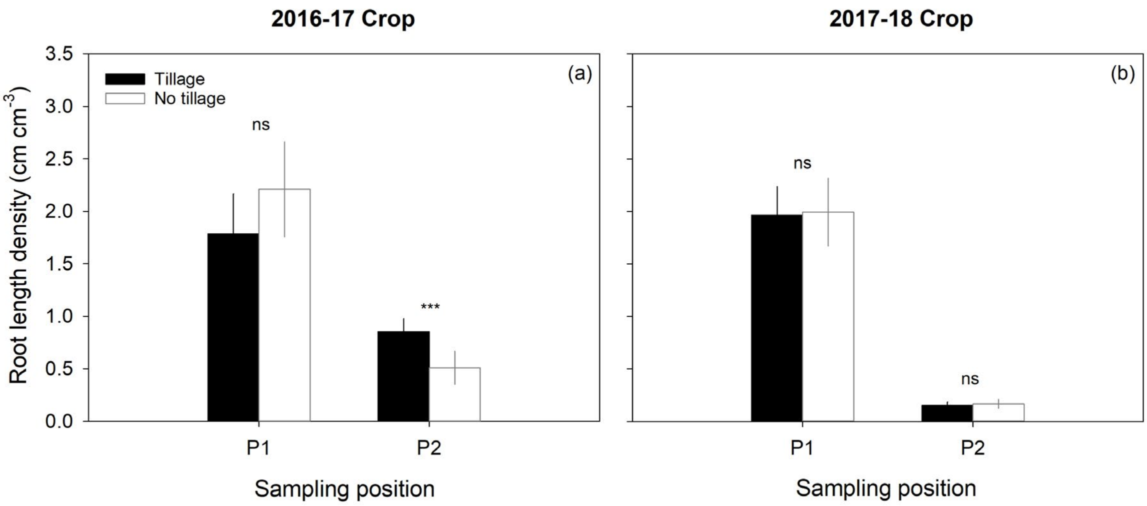

Figure 4. Root length density in the whole soil profile (0-40 cm), at 10 cm (P1) and 30 cm (P2) from the plant, in the tillage and no tillage treatments, of two sweet pepper crops grown in soil in a greenhouse. Panel (a) shows data of the 2016-17 crop, and panel (b) shows data of the 2017-18 crop. Values are means ± SE; ns, $p<0.05$; ***, $p<0.001$.

Considering that N application was consistently lower in the tillage treatment throughout the crop, this result suggests more efficient N use in the tillage treatment. Although, tillage did not result in more crop growth and yield, it apparently increased N use efficiency. To increase yield of vegetable crops in this system, it may be necessary to find the optimal combination with other cropping factors. For instance, Padilla *et al.* (2017) reported that sweet pepper yield decreased in a tillage treatment with addition of compost compared to a conventional management with no tillage. The explanation was that compost addition increased salinity (Padilla *et al.*, 2017). In other horticultural crops such as cabbage, growth and yield were similar with conventional tillage and reduced tillage (Mochizuki *et al.*, 2007).

Despite tillage may not increase yield, crop development could be affected (Jones & Popham, 1997; Unger & Jones, 1998). In compacted soils, tillage can break crusts but this may not be enough to improve physical soil properties (Primavesi, 1982). Another possible explanation proposed by Wang *et al.* (2015) for the no effect of tillage on yield is that there may be other factors, such as irrigation, that condition yield more than tillage itself. In extreme cases, soil resistance can limit root growth and reduce crop yield regardless of soil moisture status (Whalley *et al.*, 2008).

Tillage had little effects on root length density and relative root length distribution in both crops. The only effect detected was higher root length density at 30 cm from the plant (*i.e.*, at the P2 sampling position) in the first crop, which would indicate that tillage favoured horizontal root extension. Root penetration in the soil profile has been shown to decrease when the soil bulk density exceeds 1.6 kg L^{-1}, but this effect is dependent on soil moisture (Primavesi, 1982). In the present study, tillage reduced soil bulk density from 1.70 to 1.60 kg L^{-1}, which could still be excessive for root penetration.

In contrast to the present study, previous work in “enarenado” soils in Almería greenhouses reported that tillage decreased root density in the gravel mulch layer (0-10 cm depth) and increased root density in the 10-20 cm soil layer (Castilla, 1986; Martinez, 1987; Padilla *et al.*, 2017).

Table 2. Values of aboveground dry matter, fresh fruit yield and crop N uptake, and results of t-tests between the two treatments (tillage and no tillage), of two sweet pepper crops grown in soil in a greenhouse. Within each crop and variable, different lower-case letters indicate significant differences between treatments at $p<0.05$. Values are means ± SE.

Crops	Treatment	Dry matter (t ha^{-1})	Yield (t ha^{-1})	N uptake (kg N ha^{-1})
2016-17	Tillage	15.3±0.7a	91.5±4.2a	418.8±21.7a
	No tillage	13.7±0.8a	89.4±4.2a	365.1±24.3b
2017-18	Tillage	10.6±0.1a	61.0±1.7a	274.5±11.3a
	No tillage	11.2±0.3a	62.0±5.5a	289.5±2.9a

Table 3. Results of analysis of variance (ANOVA) testing the effect of tillage, sampling position and soil layer, on root length density and relative root length distribution, of two sweet pepper crops grown in soil in a greenhouse.

Crops	Effect	df	Root length density		Relative root length distribution	
			F-value	*p*-value	F-value	*p*-value
2016-17	Block	3	2.05	0.114	0.02	0.996
	Tillage (T)	1	41.40	<0.001	0.44	0.510
	Position (P)	1	66.53	<0.001	0.23	0.631
	Layer (L)	3	38.90	<0.001	80.04	<0.001
	T × P	1	11.84	<0.001	0.00	0.999
	T × L	3	1.97	0.126	2.46	0.069
	P × L	3	3.16	0.017	6.59	<0.001
	T × P × L	3	2.05	0.114	0.02	0.996
	Error	81				
2017-18	Block	3	0.94	0.425	0.17	0.914
	Tillage (T)	1	0.09	0.768	0.39	0.535
	Position (P)	1	275.31	<0.001	1.72	0.192
	Layer (L)	3	25.56	<0.001	19.52	<0.001
	T × P	1	0.03	0.871	0.09	0.764
	T × L	3	0.54	0.654	1.23	0.305
	P × L	3	16.21	<0.001	4.46	0.006
	T × P × L	3	0.34	0.797	0.73	0.538
	Error	100				

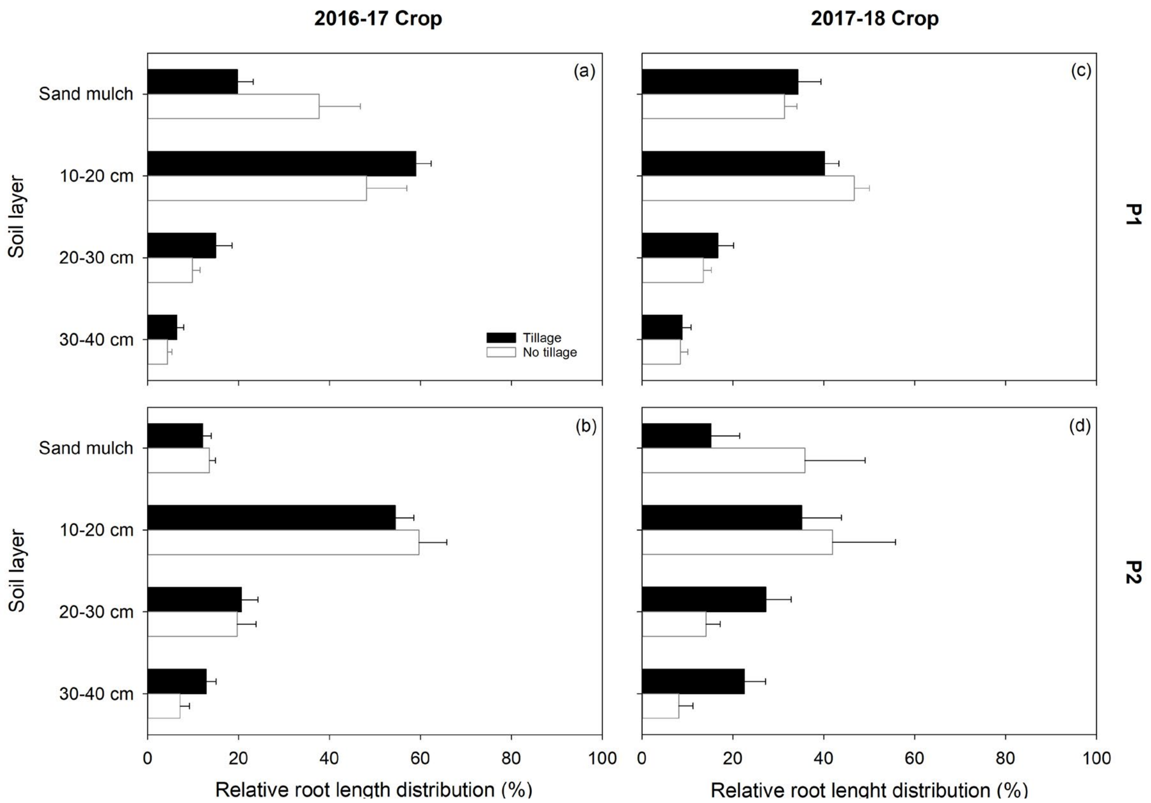

Figure 5. Relative root length distribution (%) in the two treatments (tillage and no tillage), at two sampling positions, P1 (at 10 cm from the plant) and P2 (at 30 cm from the plant), of two sweet pepper crops grown in soil in a greenhouse. Panels (a) and (b) show data of the 2016-17 crop, and panels (c) and (d) show data of the 2017-18 crop. Values are means ± SE.

Table 4. Results of repeated-measure analysis of variance (ANOVA) testing the effect of tillage and soil layer, on root length dynamics observed in minirhizotron tubes, of the 2017-18 sweet pepper grown in soil in a greenhouse.

Crops	Effect	df	*p*-value
Block (B)	3	1.19	0.344
Tillage (T)	1	0.02	0.885
Layer (L)	1	48.94	<0.001
T × L	1	0.91	0.355
Error	16		
Date (D)	12	277.15	<0.001
D × T	12	1.34	<0.197
D × L	12	8.57	<0.001
D × T × L	12	1.14	0.328
Error	192		

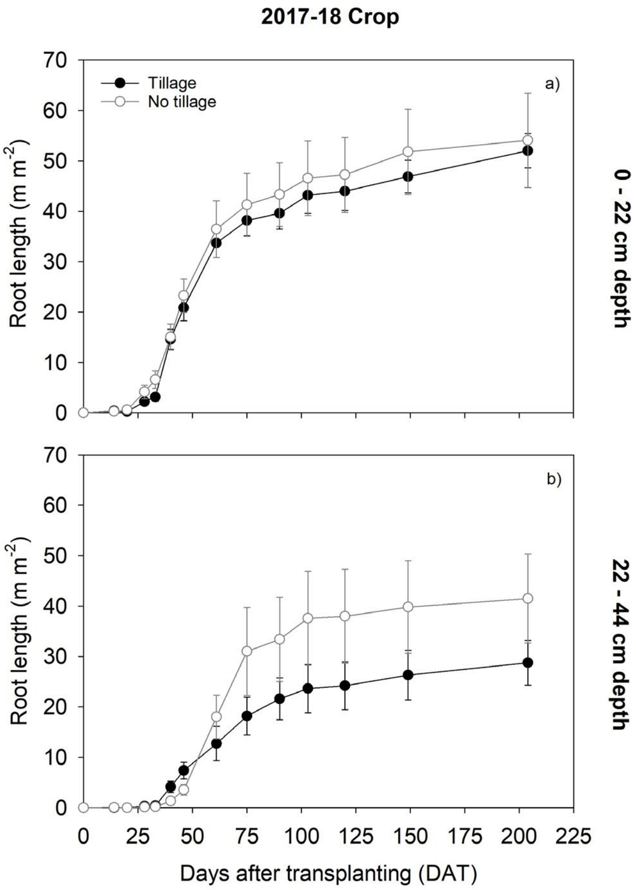

Figure 6. Root length dynamics observed through minirhizotron tubes in the two treatments (tillage and no tillage), at two soil layers, 0-22 and 22-44 cm depth of a 2017-18 sweet pepper crop grown in soil in a greenhouse. Values are means ± SE.

It is possible that in the present study that the reduction in soil penetration resistance, achieved with tillage, was not sufficient to enhance root penetration. Indeed, values of 1700 kPa of soil penetration resistance registered in the present study in the tillage treatment, at 25 cm soil depth, were notably higher than the values of soil penetration resistance of 1300 kPa reported by Erdem *et al.* (2006) at 20 cm soil depth, also with a sweet pepper crop.

Root production, estimated from minirhizotron images, were consistent with results of destructive root analysis, with no significant differences between tillage treatments. However, it is worth highlighting that there was a trend towards higher root length in the no tillage treatment in the 22-44 cm soil layer. This treatment received a greater amount of water and nutrients to reach the target soil water potential and had larger drainage volumes and more NO_3^- leaching than the tillage treatment. It is reasonable to expect that more N was located in the deeper soil layers of this treatment, and that the tendency for higher root proliferation in this layer was a response to location of N at depth (Kristensen & Thorup-Kristensen, 2007). It is possible that in this way that the interaction of tillage with other factors such as fertilization and irrigation affected the dynamics of root growth.

Overall, this study has shown that tillage did not enhance crop dry matter production or yield of either of the two cropping seasons. However, irrigation, N applied, drainage and N leaching were notably reduced with tillage, most likely due to increase infiltration capacity. In addition, tillage increased crop N uptake, increasing N use efficiency. The absence of effects of tillage on root length density and relative root length distribution, together with the slight reduction in soil bulk density and high values of soil penetration resistance, suggest that soil compaction was little affected by tillage. In "enarenado" soils, tillage is problematic because the layer of gravel mulch must be removed prior to tilling. Results of the present study suggest that the tillage applied in the experimental greenhouse is not justified in terms of improved crop growth, yield and root production.

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