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The influence of soil compaction and conservation tillage on sunflower's (*Helianthus annuus* L.) below ground system

Influencia de la compactación del suelo y laboreo de conservación en el sistema radical de *Helianthus annuus* L.

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Abstract. Soil compaction represents an important issue in the actual context of agricultural system sustainability. Research on the various developments of root systems under tillage has been explored for many crops, whether for the biomass area or the underground, but very little concerns Sunflower (*Helianthus annuus* L.). The objectives of the study were to understand the impact of soil tillage and of the induced mechanically compacted soil on: i) sunflower's root system architecture, ii) biomass area iii) production. Two complementary experiments were realized in the south of France (France's main sunflower production area). In both experiments, increased resistance of the soil to penetration was observed, characterizing soil compaction. Under compacted soil, major changes in the sunflower's root architecture occurred (-55% of root length, -67% of root surface, and -42% of root diameter) and root system exploration was negatively impacted (assessed through the use of semivariogram). This resulted in a decrease of deep root exploration and in an increased lateral growth. Modifications of leaf surface, biomass, yield, and kernel components were also reported. Those modifications were the consequences of soil compaction, and suggest a compensatory effect under such constraint.

Keywords: Sunflower; Tillage; Soil compaction; Semivariogram; Root architecture; Biomass architecture; Yield components.

Resumen. La compactación del suelo constituye un problema importante en el contexto actual de agricultura sostenible. Los cambios en la exploración del suelo por las raíces bajo impedancias mecánicas han sido estudiados para diversos cultivos, tanto en biomasa aérea como subterránea, pero escasamente en el girasol (*Helianthus annuus* L.). El objetivo del estudio fue comprender el impacto del sistema de labranza y el impacto de la compactación inducida mecánicamente sobre i) la arquitectura del sistema radical del girasol, ii) la biomasa aérea y iii) la producción. Dos experiencias complementarias se realizaron en el sur de Francia (principal zona de producción francesa de girasol). En ambos experimentos se observó un incremento de los parámetros de caracterización de la compactación del suelo, que produjeron modificaciones de la arquitectura de la raíz de girasol (longitud, superficie, volumen y diámetro de la raíz). Del análisis del sistema radical analizado mediante geoestadística, se observó el efecto negativo de la compactación del suelo, manifestando la raíz una reducción global del volumen de suelo explorado y de la profundidad alcanzada, y un aumento del crecimiento lateral. Se observaron también modificaciones de área foliar, la biomasa, rendimiento y componentes del rendimiento. Esas modificaciones fueron las consecuencias de la compactación del suelo, y sugieren un efecto compensatorio frente a la compactación del suelo.

Palabras clave: Girasol; Labranza; Compactación del suelo; Arquitectura radical; Estructura de la planta; Componentes de rendimiento.

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INTRODUCTION

In France, over the last twenty years, changes on farming practices (specialization and intensification of crops production) have contributed to the intensification of crop rotations, like the sunflower-wheat sequence (Lecomte & Nolot, 2011). In the context where fuel prices are increasing, as are the number of croplands, conservation tillage practices are expanding quickly. These practices include different techniques such as the no-till technique (total absence of soil tillage), the strip-till technique (direct sowing, minimum tillage), the ridge-till technique (simple work done on the upper layer), and the mulch-till technique that can be shallow (15 cm depth using a field cultivator for instance) or deep (depth tillage with a subsoil cultivator). The benefits of conservation tillage are well known: reduced soil erosion, increased soil water content and biological activity (Raper et al., 1994; Raper, 2005) can be mentioned among others. Soil compaction is usually characterized by a loss of the soil's macroporosity, a decrease in water and nutrient availability, an increase of the soil's bulk density, and an increase in the soil's penetration resistance (SPR) to roots (Hankansson & Lipiec, 1999; Lipiec & Hatano, 2003). Shallow and/or subsoil compaction due to agricultural traffic, in interaction with soil type, climate and cropping system, has been reported in many areas and on many crops (Lipiec & Stepniewski, 1995; Moreno et al., 1997; Taboada et al., 1998; Raper & Kirby, 2006; Taboada & Alvarez, 2008).

As for other annual rain fed crops, sunflower production (*Helianthus annuus* L.) is the result of complex interactions between genotype, crop management and of course the environment, water being the main limiting factor (Merrien et al., 1981a; Merrien et al., 1981b; Merrien & Milan, 1992). Only a small volume of the topsoil is explored by crop roots during a growing season (Maertens & Bosc, 1981). The success of water and nutrient absorption largely depends on the contact with the soil matrix and on the soil's bulk density (Lipiec & Stepniewski, 1995). The sunflower's root system is composed of a tap root and of lateral roots, which can extract more water than most other crops, specifically from deep underground. The sunflower's tap root can easily react negatively when facing a growth obstacle (Aguirrezabal & Tardieu, 1996). Several authors observed a decrease of leaf area (up to 65%, Andrade et al., 1993), plant height (up to 29%, Moreno et al., 1997), root length (up to 86%, Rosolem et al., 2002) and final yield (up to 68%, Diaz-Zorita, 2004), in response to soil compaction. Soil compaction also affects root growth for many crops, as shown by a vast number of published works (maize: Tardieu & Manichon, 1987a; Tardieu & Manichon, 1987b; cotton: Raper et al., 1994; wheat: Beemster et al., 1996; pea: Bengough, 1997; banana tree: Lecompte et al., 2003; Sadras et al., 2005; Bengough et al., 2006; soybean: Sweeney et al., 2006; Taboada & Alvarez, 2008; sugarcane: Usaborisut & Niyamapa, 2010).

It is interesting to note that among those studies, only six were conducted on sunflower crops (Halvorson et al., 1999; Aguirrezabal et al., 2003; Diaz-Zorita, 2004; Murillo et al., 2004; Aboudrare et al., 2006; Sessiz et al., 2008). Not a single one of them studied the root system architecture. A multi-location trial was conducted during years 2009 and 2010 to quantify the impact of soil compaction on the growth and development of the sunflower's root system. As results of tillage conservation practices and/or soil compaction, three complementary hypotheses of physical modifications were studied: a) root system architecture and exploration changes, b) decrease of the aboveground crop growth and development, and c) decrease of the plant production quantity and of the oil quality.

MATERIALS AND METHODS

Experimental design. Two complementary experiments were successively conducted in 2009 for field A and in 2010 for field B. For both experiments, an hybrid of sunflower with good yield plasticity under abiotic stress was seeded: 1780 degree/days base 6 from sowing to stage 5.3 (Hutley-Bull, 1995; Syngenta MELODY).

For field A, in 2009, the experiment was conducted on the experimental farm of the E.I. Purpan (Lamasquère, Midi Pyrenees, France, 43° 30' 11.75" N; 1° 14' 54.53" E) on a well-drained Glossaqualf soil (U.S.D.A United States Department of Agriculture, 1999) of the Boulbène Series. The soil type called "Boulbène" is very unstable and hydromorphic, with a water holding capacity of about 1.4 mm per cm of soil due to an important rate of pebbles (over 40% of soil volume). It has three horizons: i) 0-20 cm, (Clay: 24.3, Silt: 45.1; Sand: 30.8, SOM: 3.3, pH: 6.4); ii) 20-40 cm, (Clay: 25, Silt: 44.5, Sand: 30.4, SOM:2.7, pH: 6.15); iii) after 40 cm depth: a petroferric horizon (U.S.D.A United States Department of Agriculture, 1999) almost impossible for the roots to enter . This shallow soil has been chosen in order to expose plants to water stress under non-irrigated conditions. For this soil, two adjacent tillage treatments were compared (four replicates in each plot; plots of 1297 m^2): a) minimum tillage (zero tillage, cover crop in spring, MT); and b) triple tillage (cover crop followed by three perpendicular subsoiler passes at 60 cm depth in the spring, TT). The soil was tilled on May 5th, 2009 and the crop was planted on May 6th, 2009 (6.5 plants/m^2, 0.8 m between each row).

For field B, in 2010, the experiment was conducted in Auzeville-Tolosane (field B, Auzeville-Tolosane, Midi Pyrenees, France, 43° 32' 35.1" N; 01° 30' 02.7" E). The trial was set up in a Mollic Udifluvent soil (U.S.D.A United States Department of Agriculture, 1999). This soil was chosen for its contrasting properties with the preceding experiment. It has low stress properties under the absence of irrigation and, due to its composition (no pebbles) and the proximity with the "Canal du Midi" and the "Hers" river. It is a stable soil with four horizons: i) 0-30 cm, (Clay: 42.7, Silt: 40.7, Sand: 5.5, SOM: 2.6, pH: 8.32); ii) 30-60 cm, (Clay: 42.7, Silt: 40.6, Sand: 5.4, SOM:2.2, pH:8.38); iii) 60-90cm, (Clay: 43.2, Silt: 40.3, Sand: 4.9, SOM: 1.8, pH: 8.42); and iv) 90-120 cm, (Clay: 26.3, Silt: 59.7, Sand: 3.7, SOM: 1.6, pH: 8.48). For this soil, two adjacent soil treatments were compared (four replicates in each plot; plots of 320 m^2). The soil was tilled in autumn under good conditions on both modalities. The compacted soil modality (CS) was obtained by several wheel passes of a 3.5 ton tractor on the whole soil surface (soil moisture at 20% between 0 and 20 cm depth and 19% up to 80 cm depth, Lecompte et al., 2003). The non-compacted soil didn't receive any treatment (NCS). The soil was compacted on April 14th, the sowing done on April 27th (6.5 plants/m^2, 0.4 m between each row) and the harvest on September 20th.

During the growing season, no irrigation was applied, whether for field A (in 2009) or field B (in 2010).

As the designs used were implemented on adjacent plots, both sites received similar management before and during the experiments, except for the soil treatment (tillage for field A and compaction for field B). The replicates were implemented avoiding wheel areas, in plots of 1600 m^2 for field A (2009) and 320 m^2 for field B (2010). Therefore the authors assumed that the plots of each experiment had the same soil properties, and thus that the differences observed would be the consequences of soil treatments (Taboada et al., 1998).

Soil measurements. In both experiments, three complementary soil measures were realized during the crop cycle. For each replicate and on both treatments, soil bulk density was estimated by collecting two soil samples (cylinder of a 5 cm diameter) from a soil trench every 10 cm depth (Taboada et al., 1998; Taboada & Alvarez, 2008). The soil samples were extracted two times in 2009: on July 3rd (stage 3.4), and on August 11th (stage 5.3); and three times in 2010: on June 30th (stage 3.2), on July 29th (stage 5.0), and on September 21st (harvest date). Soil penetration resistance was assessed using a dynamic penetrometer (cone of 2 cm of diameter, Herrick & Jones, 2002; Vanags et al., 2006). The penetrometer was used three times in 2009: on June 16th (stage 2.7), on July 3rd (stage 3.4), and on August 5th (stage 5.0); and three times in 2010: on April 28th (sowing), on July 27th (stage 5.0), and on September 23rd (harvest). Each measurement was repeated twice, for each replicate, in both treatments. Soil penetration was estimated by using equation 1:

$$R = \frac{m.g.H}{a.\Delta z} \text{ x } \frac{m}{m + m^1} \quad (1)$$

where R is the resistance to the penetration (Pa), *a* is the cone basal area (m^2), g is the gravity constant (m/s^2), *m* is the hammer mass (g), *m'* is the total penetrometer mass (g), and Δz is the penetration depth (cm, Vanags et al., 2006). Gravimetric soil water content (θc) was determined in each replicate on both plots by extracting soil cores every 10 cm depth down to 60 cm three times in 2009: on June 25th (stage 3.2), on July 13th (stage 4.3), and on August 18th (stage 5.3), and in 2010: on June 30th (stage 3.2), on July 30th (stage 5.0), and on September 21st (harvest). No direct observations on soil nutrients content were monitored on the experiments.

Root system measurements. Two complementary measurements were realized in root systems in order to collect morphological and architectural data. First, in order to assess root architecture, soil trenches were sampled to evaluate *in situ* root systems profiles. Each soil trench was composed of three sunflower rows and the depth changed according to the soil type: 60 cm in 2009 and 180 cm in 2010. The root system profiles were scored at stage 4.3 on August 8th, 2009; at stage 3.2 on June 28th, 2010; and at the harvest stage on September 13th, 2010. In each soil trench, a one cm^2 grid was used to assess root length (in cm), using equation 2 (Tennant, 1975):

$$R = \frac{11}{14} x\, N \quad (2)$$

where *R* is the root length, *N* the number of root interceptions, and 11/14 the conversion factor for a one cm^2 grid unit. The maximum root depth was characterized by direct observations on the grid. In order to assess morphological data, root systems were then extracted at the harvest stage, both on the row and on the inter row. This was made after cutting, for each replicate of both plots of each experiment, the above ground part of three consecutive plants. For this purpose, an electric auger of 50 cm deep and 10 cm width was used to collect cylinders containing soil and roots for each replicate of both modalities (Scheiner et al., 2000; Becel, 2010). Roots were washed and sifted on a 2 mm grid. Measurements of extracted root systems were obtained from photographs (Nikon coolpix), cleaned using GIMP (2.6) and finally analyzed using Winrhizo (2009a, Régent Instruments Canada). This software made it possible to extract data for root surface (cm^2), root length (cm), root volume (cm^{-3}), number of forks and average root diameter (mm). These data were obtained for the total amount of root in the cylinder and the total amount of root depending of their diameter. Ten different categories were computed according to root diameter: from a diameter of 0 to more than 4.5 mm. These categories were then each divided 0.5 mm per 0.5 mm.

Above ground measurements. The evolution of leaf surface was estimated from floral bud emergence to maturity. In 2009, leaf area (LA) was estimated measuring the width of leaves on ten consecutives plants per plot (Pereyra et al., 1982; Sadras et al., 1993), using the equation 3 (Rouphael et al., 2007):

$$LA = 6.72 + W^2 \times 0.62 \quad (3)$$

where LA is the leaf area surface (m/m^2) and W the leaf width (mm). This equation was previously validated for NK-MELODY using data from a controlled experiment and the equation developed by Casadebaig et al. (2008) (linear regression, R^2: 0.98, RMSE: 0.003, $P<0.0001$). In 2010, leaf area index was estimated by using an LAI-meter (LI-Cor Inc., 1992).

At harvest, in each field, ten consecutives plants per plot were sampled. Plants above and belowground organs (root, stem, leaf, head, grain) were cleaned, separated and characterized. The organs dry matter was obtained by oven-dried at 70 °C (leaf, stem and root system), and at 45 °C for kernels, during 72 hours. Measures on all vegetative systems and yield components were obtained directly. The number of grain per head was obtained by overlapping previous data. The seed oil quality was obtained from milled sunflower grain samples (20 g, three sub-samples per plot), by near infrared spectroscopy (FOSS NIR System 6200; Ayerdi Gotor et al., 2007; Niewitetzki et al., 2007; Haddadi et al., 2010). For each sample, the reflectance value was measured from 400 nm to 6200 nm at an interval of 2 nm.

Data analysis. Data were analyzed using a two way analysis of variance (ANOVA, Rgui 2.12.0). In each experiment, each variable was compared between treatments, replications and their interactions were analyzed. A Student-t test was performed when differences were significant at the $P<0.05$ level. The analyses were carried out for each depth of reference (5 cm for root system, 10 cm for bulk densities and soil water content; 2 cm for soil penetration resistance).

Soil trenches data were also analyzed using semivariograms, and then modelized using a kriggeage approach (Jackson & Caldwell, 1993a; Jackson & Caldwell, 1993b; Ferrero et al., 2005; ArcMap.10, 2010; Mirleau-Thebaud, 2012). Geo-statistics were used to assess the root's structural variance in each soil trench, according to soil treatments. The root intersections points for a given soil treatment by soil trench, were ranked and averaged by plant and treatment replication at the same grid position (440 at stage 4.3 in 2009, 5306 at stage 3.2 in 2010, 7142 at harvest in 2010). A semivariogram was carried out, then a kriggeage of root interception on the grid for each soil treatment in each trial (type: ordinary, output: prediction) was realized. The structural variance (c) was determined by the equation 4 (Jackson & Caldwell, 1993b):

$$c = \frac{(C - C0)}{C} \qquad (4)$$

where C0 is the nugget (Y intercept of semivariogram) and C is the sill (Y value when semivariogram reaches a plateau).

RESULTS

Growth conditions. During the growing cycle, mean temperatures were 20.3 °C for field A and 19.2 °C for field B (Fig. 1). No heat stress was observed in either experiment. Cumulative rainfall was lower in 2009 than in 2010 (respectively 105 mm against 365 mm, mainly at the beginning of the crop's growth: from stage 1.1 to 2.7, and from stage 5.3 to harvest, Fig. 1).

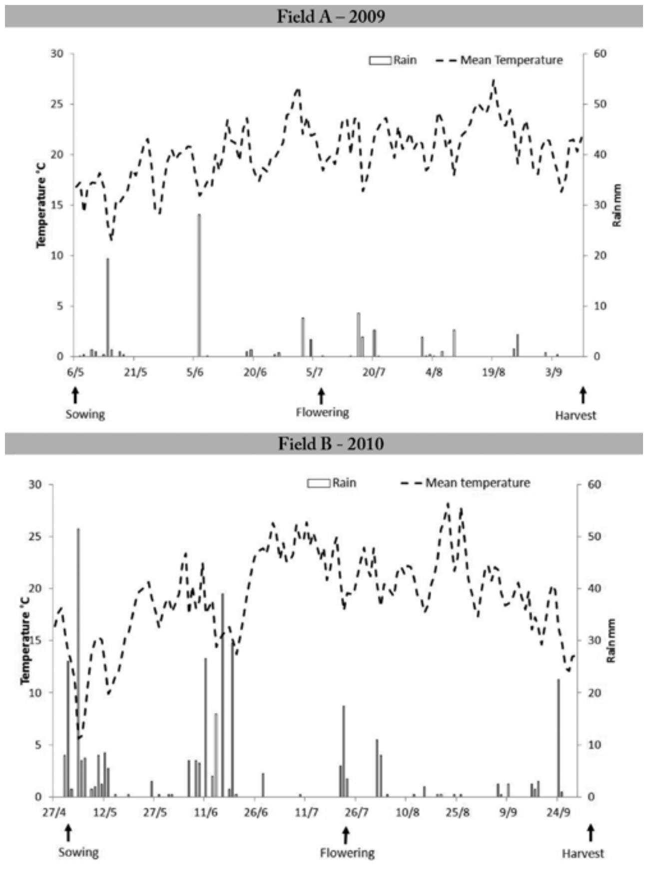

Fig. 1. Daily meteorological conditions during the growing season [from sowing to harvesting recorded at the weather station of the experimental farm of E.I. Purpan (CESBIO, 2009), and on the INRA experimental farm (2010). Mean temperature, °C, dash line; daily rain, mm, histogram].

Fig. 1. Condiciones meteorológicas diarias durante la estación de crecimiento [desde la siembra hasta la cosecha, registradas por una estación meteorológica de la chacra experimental de E.I. Purpan (CESBIO, 2009), y en la chacra experimental INRA (2010). Temperatura promedio, °C, línea cortada; lluvia diaria, mm, histograma].

Tillage effects on soil properties. No significant differences in soil bulk density between treatments were observed in field A or in field B (Fig. 2). In our experimental context, depending on the date and the depth, the cone index ranged between 1 to 11 MPa (Fig. 2) and significant differences between treatments were observed in soil penetration resistance. In field A, at stage 5.0 the TT treatment had higher penetration resistance in deep soil than in the top soil, and a significant difference was observed between the treatments in the topsoil (at 4 cm depth, P<0.05, Fig. 2). In field B, non-compacted soil presented a lower value of soil penetration resistance both at the surface and in depth (from -6 cm to -30 cm, from P<0.01 to P<0.1, at stage 5.3).

Effect of soil tillage and soil compaction on root system architecture and exploration. In field A and B, no significant differences in root abundance were obtained from the inter-row roots extractions. For both fields, a major part of the root system was located in the top soil, before 40cm depth (for field A, 94% at stage 5.0; and for field B, 99% at stage 3.2 and 96% at harvest). The maximum root systems depth was 47 cm depth

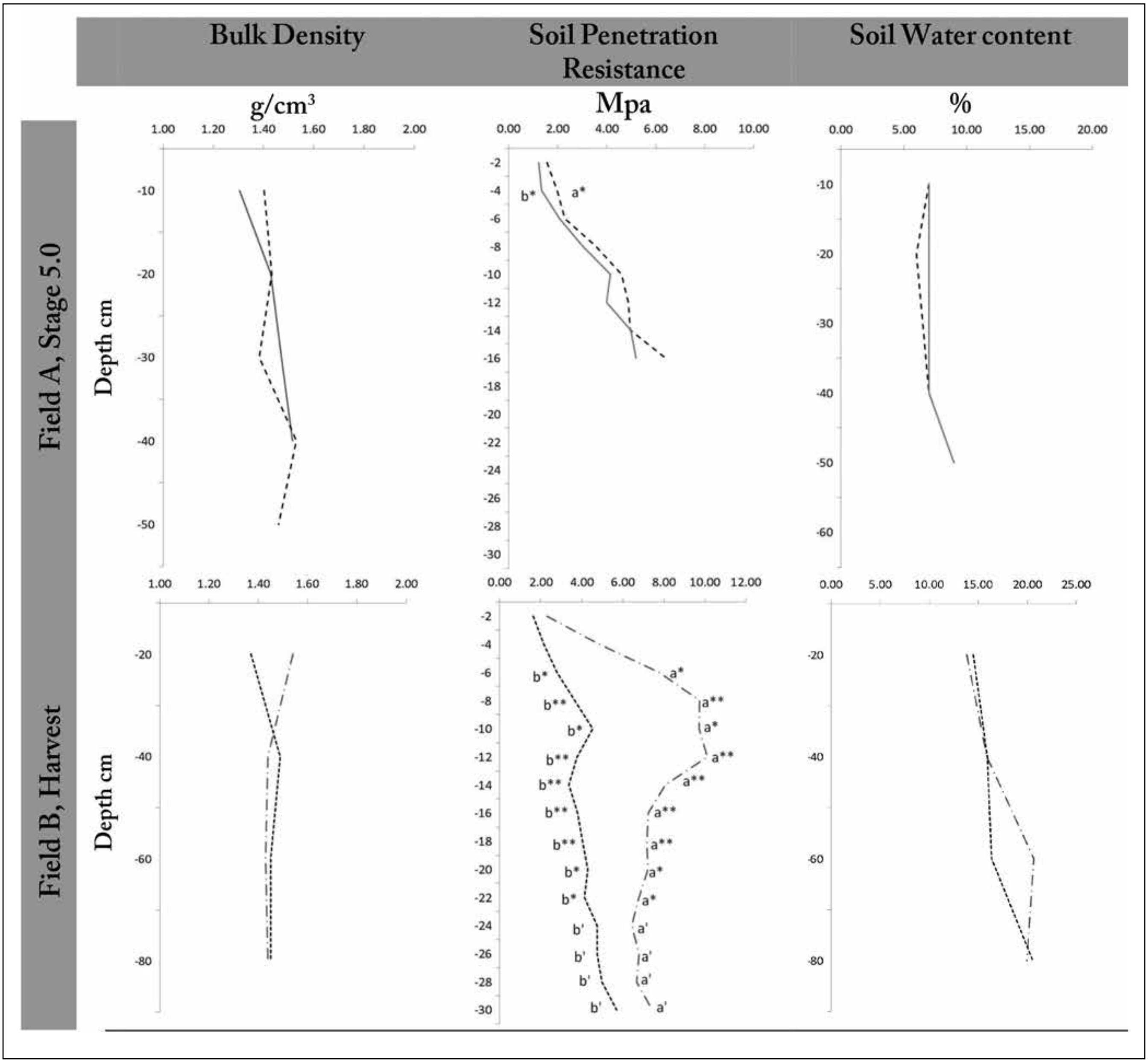

Fig. 2. Soil bulk density, penetration resistance and water status of field A at stage 5.0 and field B at harvest. In 2009, —: Minimum tillage; - - - : Triple Tillage. In 2010, — ▪ —: Compacted Soil; ▪▪▪: Non-compacted Soil. a, b: homogenous group according to student test; ' Difference Probability at 0.1; * Significant Probability at 0.05; ** Significant Probability at 0.01; *** Significant Probability at 0.001. Effectives: 18 points of measures.

Fig. 2. Densidad de suelo, Resistencia, a la penetración y nivel hídrico del campo A en el estado 5.0; y del campo B en la cosecha. En 2009, —: laboreo mínimo; - - - : laboreo triple. En 2010, — ▪ —: suelo compactado; ▪▪▪: suelo no compactado, a, b: grupo homogéneo de acuerdo al test de Student; Probabilidad de diferencia a 0,1; * Probabilidad significativa a 0,05; ** Probabilidad significativa a 0,01; *** Probabilidad significativa a 0,001. Efectivos = 18 puntos de mediciones.

in field A, and 61 cm in field B (Table 1). No significant differences on global root system morphology were observed in field A (Table 1 and 2). In field B, both root system architecture and growth were affected by soil compaction (Table 1 and 2). Independently of root diameter class, global root system morphology presented significant decreases under CS treatments in field B: -67% of root surface (P<0.001, Table 2), -42% of root average diameter (P<0.01), -55% of root length (P<0.001), -71% of root volume (P<0.001). In field B, the maximum root length was observed for roots with an average diameter between 0.5 and 1 mm for CS and an average diameter between 1 to 1.5 mm for NCS (Table 2). Significant decreases under CS were observed for root length (for classes of all average root diameters except the finest: between 0 and 0.5 mm, P<0.01); for root surface (for classes of all average root diameters except between 0 and 0.5 mm and between 2 and 2.5 mm, P<0.01); and for root volume (for classes of all average root diameters except the finest: between 0 and 0.5 mm, P<0.001).

Significant differences between soil treatments were observed in the root profile (Fig. 3). As shown on the roots distribution according to soil depth, under MT, roots in field A were more abundant on the surface (5 cm depth, P<0.1), than in depth (45 cm depth, P<0.1). In field B, under CS, at stage 3.2, roots were more abundant in the top soil than in deep soil (P<0.05 at 15 cm, P<0.1 at 45 cm depth). At harvest, root intersections on the grid increased under NCS in deep soil (-60 cm, P<0.05).

The variability of root system exploration in soil trenches was important between soil treatment and fields (Fig. 3, Table 4). In each grid (zonal for field B and centric for field A), some anisotropy associated with depth was observed. In field A, the semivariogram showed no structural variance under TT (Table 4) and a low structural variance under MT. In field B at stage 4.3, the structural variance was relatively high for both treatments, but was lower for CS (c: 95% for CS in comparison to 96% for NCS, Table 4, and Fig. 3). Moreover, krigged root grid interception showed very different soil exploration patterns. Under CS, the root system exploration was smaller with the occurrence of an important network of lateral roots (45 cm width in NCS against 35 cm in CS). The authors assume that the longest roots observed in the results were the tap roots. In 2010, the tap roots were deeper in NCS than in CS (difference of 10 cm, Fig. 3). In the same field, at harvest, the structural variance was higher under CS (c: 92%) than under NCS (c: 73%, Fig. 3). The krigged root exploration showed changes from stage 3.2 to harvest. In both treatments, the tap roots were deeper at harvest. A decrease in root system width was also observed, highlighting a decrease in root branching between both dates, which were more important in CS than in NCS. Similar results were observed under both treatments between the two stages for tap root elongation (difference of 10 cm in favor of NCS).

Effect of soil tillage and soil compaction on above ground system architecture. For each field and for both soil treatments (MT: 1.2 m^2/plant; TT: 1.3 m^2/plant) the maximum leaf area was reached at stage 4.3.

In field A (2009), the maximum leaf area (stage 4.3) was under the optimal value (defined under the climatic context) for both soil treatments modalities (1.2 m^2/plant, Fig. 4). In field B (2010) from stages 4.1 to 5.1, the leaf area index was higher than the optimal with a maximum reached at stage 4.1 (CS: 3.6 m^2/plant; NCS: 3.5 m^2/plant).

Table 1. Effect of tillage on root systems architecture at harvest. Field A and B. Means of roots system measurements: results from mean comparison after analysis of variance.
a, b: homogenous group according to Student test; ' Difference Probability at 0.1;* Significant Probability at 0.05; ** Significant Probability at 0.01; *** Significant Probability at 0.001; - Absence of significant differences. Effectives: 72.
^{c}: standard deviation.
Tabla 1. Efecto de la labranza en la arquitectura de Sistema radical a la cosecha. Campos A y B. Promedios de las mediciones en el sistema radical: resultados de la comparación de medias después del ANOVA.
a,b: grupo homogéneo de acuerdo al test de Student; * Probabilidad de diferencia a 0,1; ** Probabilidad significativa a 0,01; *** Probabilidad significativa a 0,001; - Ausencia de diferencias significativas. Efectivos: 72.
^{c}: desviación estándar.

	Field A - 2009		Field B - 2010	
	MT	TT	CS	NCS
Root Surface (cm^{-3})	133,1 ± 30.5^c	137,1 ± 29.3	527,7 ± 557.5 b***	1624,5 ± 358.4 a***
Root Average Diameter (mm)	2,4 ± 0.6	2,4 ± 0.5	2,2 ± 1.2 b**	3,8 ± 0.5 a**
Root Length (mm)	179,7 ± 41.2	185,3 ± 36.8	620,3 ± 294.8 b***	1374,9 ± 302.30a***
Root Volume (cm^{-3})	8,2 ± 2.6	8,4 ± 3.2	44,6 ± 65.8 b***	155,1 ± 43.2 a***
Number of root forks	556,8 ± 228.5	583,7 ± 181.5	1227,1 ± 255.3	1397,3 ± 354.6
Maximum Root depth (cm)	47.5 ± 3.5	45.0 ± 7.1	53.0 ± 0.0 b'	61.0 ± 2.8 a'

Table 2. Mean of induced compaction effect on root architecture at harvest by root class diameter, Field B, 2010.
a, b: homogenous group according to Student test; ' Difference Probability at 0.1;* Significant Probability at 0.05; ** Significant Probability at 0.01; *** Significant Probability at 0.001; - Absence of significant differences. Effectives: 12. c: standard deviation
Tabla 2. Promedio del efecto de compactación, inducido en la arquitectura de la raíz a la cosecha pro diámetro de clase de raíz, campo B, 2010.
a,b: grupo homogéneo de acuerdo al test de Student; ' probabilidad de diferencia a 0,1; * Probabilidad significativa a 0,05; ** Probabilidad significativa a 0,01; *** Probabilidad significativa a 0,001; - Ausencia de diferencias significativas. Efectivos: 12.
c: desviación estándar.

Root diameter Class	Soil Treatment	Root Length (mm)	Root Surface (cm^2)	Root Volume (cm^{-3})
From 0 to 0.5 mm	CS	146.5 ± 63.1^c	14.4 ± 5.2	0.1 ± 0.0
	NCS	128.4 ± 42.6	14.8 ± 4.9	0.1 ± 0.0
From 0.5 to 1 mm	CS	156.1 ± 34.8 b**	36.0 ± 8.1 b**	0.7 ± 0.1 b***
	NCS	203.4 ± 49.6 a**	46.2 ± 9.8 a**	0.9 ± 0.2 a***
From 1 to 1.5 mm	CS	122.1 ± 117.3 b***	48.3 ± 46.3 b**	1.5 ± 1.5 b***
	NCS	375.7 ± 106.81 a***	148.1 ± 45.0 a**	4.7 ± 1.3 a***
From 1.5 to 2 mm	CS	51.1 ± 46.9 b***	28.4 ± 26.4 b**	1.3 ± 1.2 b***
	NCS	131.1 ± 38.2 a***	73.6 ± 21.4 a**	3.3 ± 0.9 a***
From 2 to 2.5 mm	CS	15.1 ± 56.7 b***	31.9 ± 39.7	1.8 ± 2.2 b***
	NCS	151.3 ± 50.3 a***	106.5 ± 35.3	6.0 ± 1.9 a***
From 2.5 to 3 mm	CS	18.5 ± 21.7 b***	16.3 ± 19.4 b**	1.1 ± 1.4 b***
	NCS	68.1 ± 19.8 a***	60.2 ± 17.5 a**	4.2 ± 1.2 a***
From 3 to 3.5 mm	CS	12.3 ± 14.8 b***	12.7 ± 15.3	1.0 ± 1.3 b***
	NCS	52.6 ± 14.4 a***	54.6 ± 14.9	4.5 ± 1.2 a***
From 3.5 to 4 mm	CS	9.1 ± 10.9 b***	10.5 ± 12.7 b***	0.9 ± 1.2 b***
	NCS	40.9 ± 8.7 a***	47.7 ± 70.3 a***	4.4 ± 0.9 a**
From 4 to 4.5 mm	CS	6.9 ± 9.1 b***	9.3 ± 12.1 b***	0.9 ± 1.3 b***
	NCS	40.0 ± 11.5 a***	53.6 ± 15.6 a***	5.7 ± 1.7 a***
Above 4.5 mm	CS	52.2 ± 55.2 b***	258.6 ± 320.8 b***	202.1 ± 315.4 b***
	NCS	175.3 ± 41.0 a***	814.7 ± 222.8 a***	606.8 ± 275.5 a***

In field A, during all the crop cycle, the triple tillage presented a lower leaf surface index compared with the triple minimum treatment. At stage 5.0, this decrease of leaf surface represented 8.5% and at stage 5.3, it represented 4.8% ($P<0.5$, Fig. 4). In field B (2010), no significant differences were reported between CS and NCS.

Maximum plant height was highest in field B (mean of 179 cm), than in field A (mean of 119 cm, $P<0.001$, Table 3). At the beginning of the cycle, in 2009 (field A, stage B5), the plants were smaller under MT than under TT (-14.6%, $P<0.5$, Table 3). At the stages 5.0 and 5.3, the situation was reversed with an increase of 3.5% and 11.8%, respectively, under MT ($P<0.5$, Table 3). In field B, no significant differences were observed between the two treatments. In our experiments only leaf biomass presented a significant difference between both treatments in field A ($P<0.05$, Table 3).

Effect of soil compaction and conservation tillage on yield component. The kernel biomass was higher in field B than in field A (188.5 g against 347.5 g, $P<0.001$; Table 3). In field A, under MT, the weight of thousand grains was 15 % ($P<0.05$) smaller than under TT (Table 3). Seed dry matter and oil content presented an increase in 2010 in comparison with 2009 (means = 95.85% against 95.6%, and 49.6% against 44.9%, respectively, $P<0.001$; Table 3). In 2010, no differences between the treatments were observed on dry matter or on oil content. The grain protein content, which was not significant in 2010, presented a decrease under MT in 2009 (-6%, $P<0.5$, field A). The oleic acid content was higher in field B than in field A (22.8% against 15.5%, $P<0.001$), and the level of linoleic acid was higher in field A than in field B (76.5% against 69%, $P<0.001$, Table 3). Field B presented a decrease of oleic acid in seeds under CS ($P<0.5$). Thus, the level of linoleic acid presented an increase under CS in the same field ($P<0.5$). No significant results were found in 2009.

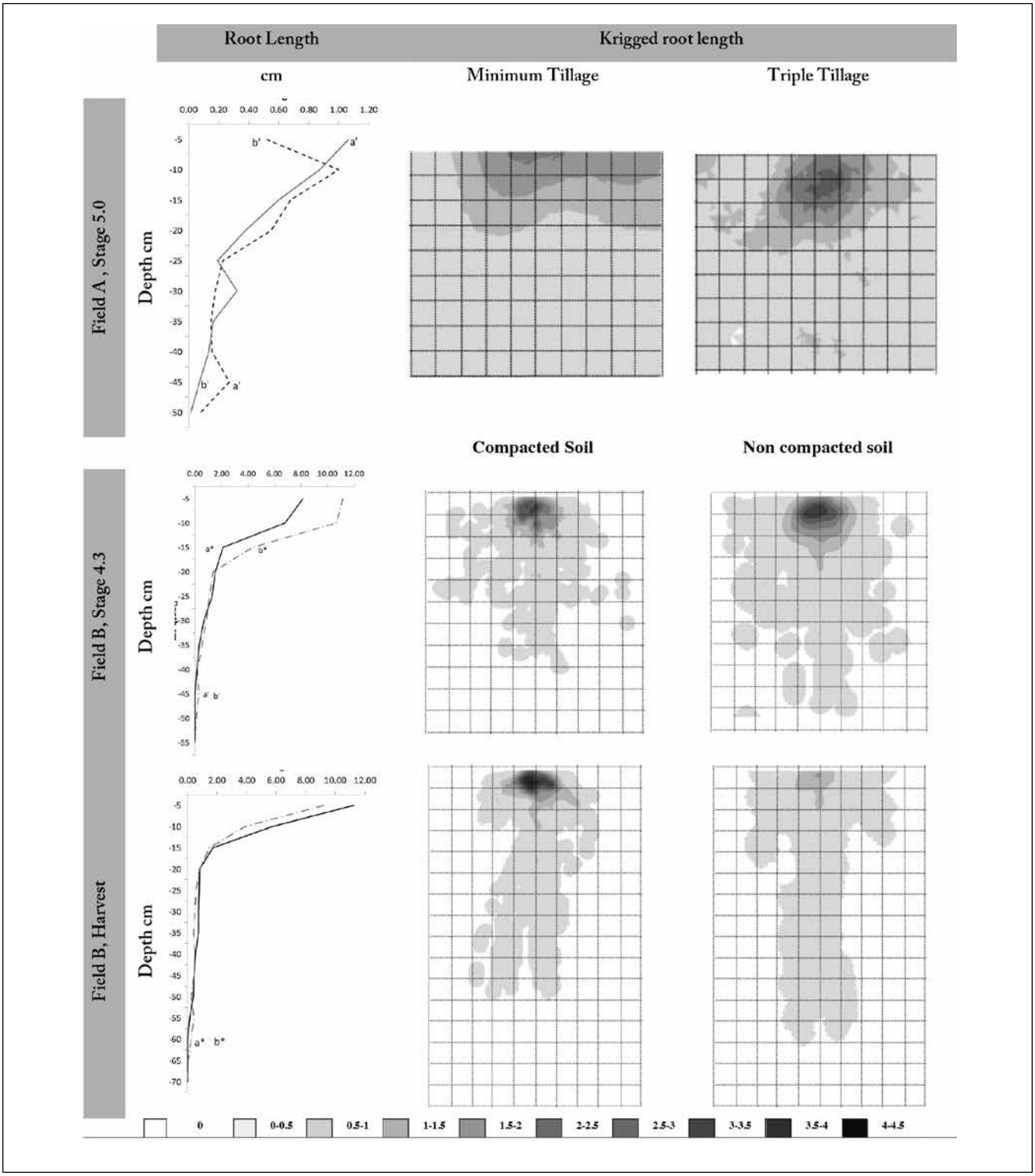

Fig. 3. Effect of soil induced compaction on root profile and exploration. Roots per square centimeter. Grid of 5 cm², X from -25 cm to 25 cm, 0: sunflower stem base, Y, from 0 to 80 cm depth. Data calculated from grid intersection (5 cm²) with Tennant method (Tennant 1975). Kriggeaged data: root length cm; statistic: see table 4.

Fig. 3. Efecto de la compactación del suelo inducida en el perfil y exploración de raíces. Raíces por cm². Malla de 5 cm², X desde -25 cm a 25 cm, 0: base de tallo de girasol, Y, desde 0 a 80 cm de profundidad. Datos calculados desde la intercepción de malla (5 cm²) con el método de Tennant (Tennant, 1975). Estimaciones de Kriggeaged de datos: longitud de raíces, cm; estadística: ver Tabla 4.

Table 3. Effect of tillage on plant above ground biomass, yield component and kernel quality. Results from means comparison after analysis of variance. In 2009: Minimum tillage, Triple Tillage. In 2010: Compacted soil, non-compacted soil. Effective: 80. a, b: homogenous group according to Student test; ' Difference Probability at 0.1; * Significant Probability at 0.05; ** Significant Probability at 0.01; *** Significant Probability at 0.001. c: standard deviation.
Tabla 3. Efecto de la labranza en la biomasa aérea de las plantas, los componentes del rendimiento y calidad de granos. Resultados de la comparación de medias después del ANOVA. En 2009: Labranza mínima, Labranza triple. En 2010: Suelo compactado, suelo no compactado. Efectivo: 80. a,b: grupo homogéneo de acuerdo a la prueba de Student; ' Probabilidad se diferencia a 0,1; * Probabilidad significativa a 0,05, ** Probabilidad significativa a 0,01; *** Probabilidad significativa a 0,001. c: Desviación estándar.

		Field A, 2009		Field B, 2010	
		MT	TT	CS	NCS
Above ground	Plant Height (cm)	**121.82 ± 7.8^c a***	**116.61 ± 8.13 b***	178.23 ± 5.7	178.5 ± 8.7
	Leaf biomass (g/m^2)	**74.6 ± 40.6 a***	**96.9 ± 45.9 b***	152.9 ± 114.0	164.6 ± 161.2
	Stem biomass (g/m^2)	164.4 ± 60.8	178.1 ± 63.5	284.7 ± 88.4	311.2 ± 97.7
	Kernels biomass (g/m^2)	172.1 ± 91.1	204.7 ± 114.3	336.4 ± 109.8	358.5 ± 126.9
	Total biomass (g/m^2)	656.9 ± 304.1	773.0 ± 350.9	1242.0 ± 407.5	1352.4 ± 480.9
Yield Component	Number of Kernels/head	946.4 ± 332.5	1087.5 ± 318.2	1093.8 ± 272.6	1152.5 280.6
	Weight of Thousand grain (g)	**28.8 ± 7.4 b****	**34.2 ± 8.1 a****	58.1 ± 31.0	54.8 ± 10.2
Seeds Quality	Dry Matter (%)	95.7 ± 0.4	95.5 ± 0.4	95.9 ± 0.4	95.8 ± 0.3
	Oil content (%)	45.5 ± 2.9	44.3 ± 3.4	49.5 ± 2.9	49.6 ± 1.9
	Protein content (%)	**15.2 ± 1.7 b***	**16.1 ± 1.5 a***	15.7 ± 1.3	15.6 ± 1.6
	Oleic content (%)	15.1 ± 4.1	16.5 ± 3.4	**22.2 ± 4.9 a***	**23.9 ± 5.5 a***
	Linoleic content (%)	76.9 ± 9.9	75.5 ± 3.8	**69.7 ± 4.1 a***	**67.7 ± 5.6 a***

Table 4. Model parameter for each semivariogram in Figure 3. The structural variance is the result of equation 4.
Tabla 4. Parámetros del modelo para cada semivariograma en la Figura 3. La varianza estructural en el resultado de la ecuación 4.

	Field A, Stage 4.3		Field B, Stage 5.0		Field B, Stage harvest	
Treatment	TT	MT	CS	NCS	CS	NCS
Effective	110.00	111.00	2653.00	2653.00	3571.00	3569.00
Mean	$5.90.10^{-3}$	$9.20.10^{-3}$	$5.70.10^{-4}$	$3.04.10^{-5}$	$7.16.10^{-5}$	$1.57.10^{-5}$
Standard error	0.43	0.41	0.14	0.10	0.08	0.11
Root mean square error	0.44	0.41	0.12	0.11	0.07	0.09
Coefficient of variation	72.88	44.57	245.61	3289.47	1089.39	7006.37
Nugget value, C	-	1.21	0.05	0.09	0.07	0.49
Sill, C_0	-	3.64	1.05	1.91	0.95	1.78
Structural variance	-	**0.67**	**0.95**	**0.96**	**0.92**	**0.73**

DISCUSSION

Effect of soil tillage and soil compaction on soil properties. Added to soil bulk density, soil penetration resistance and soil water content are indicators of soil strength, soil compaction, and resistance to root system growth (Herrick & Jones, 2002; Lipiec & Hatano, 2003; Becel, 2010). Soil compaction increases soil strength (Jorajuria et al., 1997; Lecompte et al., 2003; Raper, 2005; Sweeney et al., 2006 ; Lipiec et al., 2009). This phenomenon is characterized by an increased penetration resistance and bulk density, and a reduction of the plant's water availability (Lipiec & Stepniewski, 1995; Taboada et al., 1998; Lipiec & Hatano, 2003; Sadras et al., 2005). When using soil conservation techniques, Moreno et al. (1997) and Taboada and Alvarez (2008) observed the same phenomenon. This is not consistent with the present experiments, where only differences of soil penetration resistance were observed in field B. Water

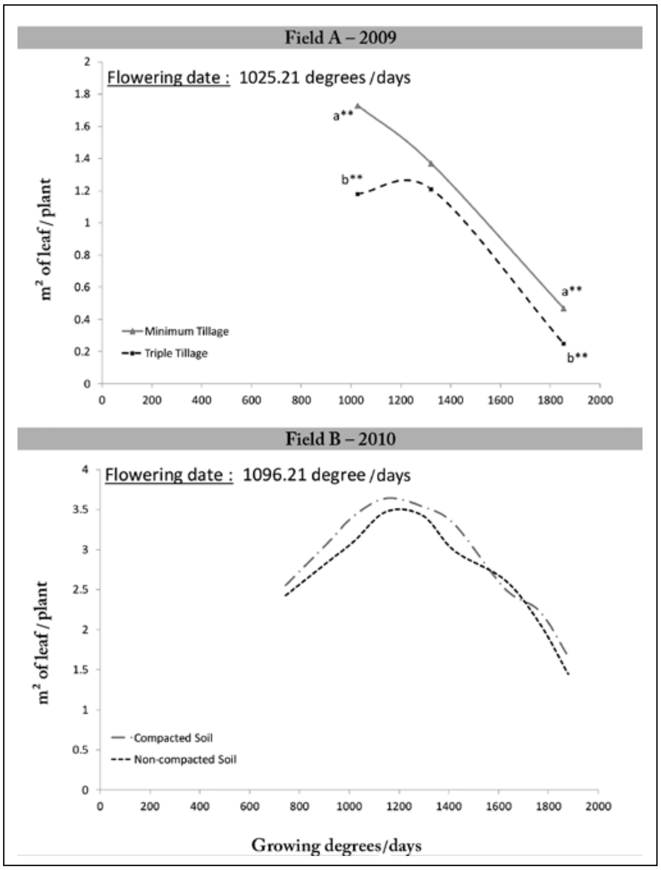

Fig. 4. Impact of soil tillage and induced soil compaction on leaf area (LA). Means of leaf area (m² of leaf/plant): results from mean comparison after analysis of variance. In 2009 LA estimated by measuring leaf width (—: Minimum tillage; - - - : Triple tillage). In 2010 LA done using a LA meter (— ▪ —: Compacted Soil; ▪▪▪: Non-compacted Soil). Effective: 80. a, b: homogenous group according to Student test; Difference Probability at 0.1,* Significant Probability at 0.05, ** Significant Probability at 0.01, *** Significant Probability at 0.00.

Fig. 4. Impacto del laboreo del suelo y compactación del suelo inducida en el área foliar (LA). Promedios de áreal foliar (m² hojas/planta): resultados de la comparación de medias después del ANOVA. En 2009, LA fue estimada midiendo el ancho de la hoja (—: Laboreo mínimo; ---: labranza triple). En 2010, LA se efectuó usando un medidor de área foliar (— ▪ — : suelo compactado; ··· : suelo no compactado). Efectivo: 80. A,b: grupo homogéneo de acuerdo al test de Student; Diferencia de probabilidad a 0.1; * Probabilidad significativa a 0,05; ** Probabilidad significativa a 0,01; *** Probabilidad significativa a 0,00.

content and soil penetration resistance seem to be inversely correlated (Busscher, 1990; Kirby & Bengough, 2002; Vanags et al., 2006; Konopka et al., 2008; Konopka et al., 2009). Under unlimited water availability, water molecules can act as a lubricant between clay particles, and therefore decrease the cohesion between particles. This can explain the lack of difference in BD between both treatments in Field B. In field A, the amount of pebbles and the low water content did not allow this phenomenon to appear, and the fast bulk density resilience was mainly due to its composition.

Effect of soil tillage and soil compaction on plant's root architecture. The main part of the root system was located in the upper part of the soil, as reported in literature (Sadras & Hall, 1989; Cabelguenne & Debaeke, 1998; Scheiner, J.D. & R.S. Lavado, 1999; Angadi & Entz, 2002). In fields and in controlled experiments, research on several crops, including sunflower, reported either a decrease of the (i) number of roots (-30% for soybeans, Micucci & Taboada, 2006); rooting depth (-40% for banana trees, Lecompte et al., 2003); root length (-80%, for sunflowers, Rosolem et al., 2002); root growth (-60% for peas, Croser et al., 2000; -40% for sunflowers, Petcu & Petcu, 2006); root biomass (-60% for sunflowers Andrade et al., 1993); water and nutrient uptake (-35% for barley, Bingham et al., 2010); and/or an increase of (ii) lateral root length (+54% for beans), root branching at the soil surface, and root diameter (+60% for peas, +16% for sunflowers). This is consistent with Field B experiments where soil induced compaction led to a loss of root volume, root surface, length, and average diameter. Considering root growth and soil exploration in the top soil, fine diameters were more important under CS than under NCS. This is inconsistent with the literature on main crops, where the global root diameter generally increases under soil compaction. However, Petcu and Petcu (2006) observed an increase of sunflower root surface in the top soil (more than 30%), obviously involving root diameter. According to Konopka et al. (2008; on maize), this increase can induce a reduction of the soil's mechanical impedance, and thus, a weakening of the soil's resistance to root growth. A decrease in the tap root's deep development was observed as the root system became larger under CS (Tardieu, 1988a; Alessa & Earnhart, 2000; Rosolem et al., 2002; Lipiec & Hatano, 2003). The structural variance of root exploration was also confirmed (Tardieu, 1988b). Thus, Field B experiment confirmed a deep modification of the root's architecture and exploration system under mechanically constrained soil. Such modifications (increase of branching, and decrease of rooting depth) could be the result of compensation processes under constrained soil as observed by several authors. (Clark et al., 2003; Lipiec & Hatano, 2003; Konopka et al., 2008). Even in this case, an alteration of root capture efficiency could be induced by the modification of the root system growth and its functioning (Croser et al., 1999; Croser et al., 2000).

Effect of soil tillage and soil compaction on the plant's aerial architecture. In France, due to unlimited water availability (rain) during the first half of the crop's cycle, and to water scarcity during its last part (flowering to maturity), the sunflower's optimum leaf area ratio has to be between 2.5 and 3 at flowering (Merrien & Grandin, 1989). In our experiments, this rate was not reached in field A, maybe because of an LA optimization in response to the soil constraints (water shortage mainly) and to the climatic conditions in 2009. At the opposite, field B overtook this level up to stage 5.1, which allowed good growth, good fertilization and a good grain filling start.

From emergence to flowering, leaves have to synthesize and redistribute reserves between the aerial and underground (mainly roots) plant parts. From the flowering period onwards, leaves have to synthesize and redistribute reserves to the aerial plant parts in order to allow grain filling and oil making (Connor & Sadras, 1992; Merrien & Milan, 1992). During grain filling, leaf duration can be altered by a loss of nitrogen in senescing leaves (Connor & Sadras, 1992). If the plants have difficulties in resource absorption efficiency because of soil compaction (Sadras et al., 2005), defoliation would increase, and thus above-ground resource acquisition would decrease (Merrien et al., 1981a; Merrien et al., 1981b). Leaf area and leaf elongation decreases are a usual plant response to a mechanically constrained soil (-30% on banana tree, Lecompte et al., 2003; -20% on wheat and barley, Beemster et al., 1996 and Bingham et al., 2010 respectively; -65% on sunflower, Andrade et al., 1993). In our experiments, a significant decrease was observed under minimum tillage in field A at the end of the cycle. Soil compaction leads to decreases in water potential and total soil available water for plants (Lipiec & Hatano, 2003). Thus, in case of soil compaction and soil water scarcity, the plant would have more difficulties to capture water resources. At the opposite, if soil compaction is not strong enough to slow suitable shoot growth rate, an increase of soil compaction would then lead to a favored root contact with the soil matrix, and thus to a better water absorption. Since the leaves are the main organs for resource synthesis, and the main source of resource partitioning, a decrease of leaf area would have consequences in plant growth and final production. As observed in our experiments, a plant height decrease under compacted soil is also known to be a plant response to a mechanically constrained soil (-10% for sunflower, Petcu & Petcu, 2006; -10% for soybean, Sweeney et al., 2006). The difference of plant height in field A, but not in field B, was caused by the same phenomenon.

Effect of soil compaction and conservation tillage on yield component and oil quality. Biomass is one indicator of plant nutrition during its cycle. Under soil compaction, a loss of biomass of every plant organ and then a loss of total biomass is observed in many areas and for a lot of crops (-40% on soybean, Sweeney et al., 2006; -50% on barley, Bingham et al., 2010). Bingham et al. (2010), associated this decreased biomass with a lower nitrogen input (leading also to a reduction of leaf area). In our experiments, at harvest, only the leaf biomass presented a significant decrease under MT. This is consistent with the loss of leaf area which is established at the floral initiation, and then results from cell elongation (Tardieu, 1994). Cell elongation decreases as soil compaction increases (Beemster et al., 1996). This is associated with the decrease of cell length at the stage of resource partitioning; reflecting an alteration of resource use efficiency. In field B, a non-significant decrease of biomass, and a non-significant increase of LA, could have occurred due to a suitable soil water status allowing good growth conditions under soil compaction (Tardieu, 1994; Lipiec et al., 2003), without any action of leaf cell elongation. A deeper study of the soil's compaction impact and growth kinetic at the first plant development stages could confirm if those facts (in each experiment) were the result of a reduction of crop production caused by either physiological issues, a "mechanical" reduction (Tardieu, 1994), or a phenological delay, as argued by Andrade et al. (1993). In both cases, this succession of events would act on final yield.

Yield decreases of up to 68% on sunflower under soil compaction have been reported in the literature (Diaz-Zorita, 2004). Final yield is the result of complex interactions during the crop cycle, which are traduced in the following main yield components: size of a productive plant population, number of kernel by head, and weight of thousand grains.

A thousand grain weight is an indicator of the plant capacity for grain filling. On sunflower, contrasting results have been reported under soil compaction (decrease: Sojka et al., 1990; increase: Heidari Soltanabadi et al., 2008). Grain filling is directly linked to foliar state duration after flowering (Merrien & Milan, 1992). Negative relations between soil water status and number of florets have been reported (Connor & Sadras, 1992). To carry out those observations, strong drought stress has to be realized (Merrien et al., 1981b). Due to meteorological conditions, no severe drought stress symptoms were observed in the fields. However the pedoclimatic conditions at field A associated with soil tillage were consistent. Under these conditions, plants may have favored the thousand grain's weight rather than the number of kernel by heads as a survival strategy (Moroke et al., 2011). At the opposite, under much favorable soil water conditions, the greater seed mass at the CS treatment in field B, confirms a better water and nutrient use efficiency during grain filling (Moroke et al., 2011).

A decrease of sunflower oil under soil compaction has been reported in the literature (Sojka et al., 1990; Petcu & Petcu, 2006). No significant results have been reported on any field. Oil accumulation is optimal under good climatic conditions (temperature superior to 25 °C, not exceeding 35 °C, and 25 days after anthesis, Rondanini et al., 2003; 2006). This was the case for fields A (2009) and B (2010). Protein synthesis is carried out first, just after anthesis (Connor & Sadras, 1992). During grain filling, sunflower has been shown to favor synthesis of proteins rather than oil or fatty acids under stress conditions, because of their energetic cost (Merrien & Milan, 1992). Under soil compaction, Sadras et al. (2005) observed an increase of 6% of grain protein in wheat. The greater level of grain protein under TT in field A, confirms the N and water deficiency during grain filling.

A significant decrease of oleic acid, and a significant increase of linoleic acid, were observed at field B in 2010. Even if, among various environmental factors, temperature is the main source of fatty acid variations, other environmental factors (such as intercepted solar radiation, nitrogen availability, water supply and management practices) also act on their synthesis pathways, and subsequently on their content (Aguirrezabal et al., 2009; Echarte et al., 2010). Soil compaction's negative influence has been reported on leaf area (Tardieu, 1994; Passioura, 2002; Lecompte et al., 2003), and therefore on intercepted solar radiation (Sadras et al., 2005). Studies on changes in fatty acid content due to environmental conditions remain controversial. Variations of fatty acids under soil tillage have been reported (Mirleau-Thebaud et al., 2011). Fatty acid variation linked to water management systems have also been reported in the literature (Roche et al., 2006; Haddadi et al., 2010). Irrigation and a slight drought stress (Baldini et al., 2002) can favor oleic acid content (Flagella et al., 2004; Roche et al., 2006; Haddadi et al., 2010). The D12 desaturate activity (enzyme involved in the desaturation of oleic to linoleic acid; Garces et al., 1989) is directly related to water deficit (Roche, 2005). The regulation of this enzyme could allow the plant to adapt itself to water scarcity by maintaining membrane function under drought (more saturated fatty acids in membrane lipids lead to sustained membrane fluidity) (Roche, 2005; Roche et al., 2006). Soil compaction affects soil water availability, and therefore could have indirectly acted on the D12 desaturase.

CONCLUSION

In our study, soil type and minimum tillage induced compaction with increased values of soil resistance to penetration. Despite the two designs used to assess soil compaction, the two types of soil reacted differently, due to their properties. The soil compaction observed in Field B (2010) had several direct and indirect consequences on sunflower. The aboveground and the underground architecture changes observed were the direct and indirect consequences of soil compaction. Under soil-induced compaction, a decrease of rooting depth, root surface and root average diameter was obtained while an increase occurred in the root number of forks. Those changes led to growth, reproduction, and final plant production alterations. These alterations of root system growth and exploration suggest a compensatory response of the root system under soil mechanical constraint. Since soil conservation practices tend to increase in the French context, as elsewhere, our results would have to be taken into account.

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