Systemic analysis of soil compaction and conservation tillage effect on sunflower (*Helianthus annuus* L.) development and nutrition

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ABSTRACT

- The strong demand of oleic oil for human feeding but also for industrial purpose emphasized the need for a high and regular level of oleic acid content in sunflower (*Helianthus annuus* L.) crops in the French context. Its production is the result of complex interactions between the genotype, the crop management and the environment. Only a part of the top soil is explored by the root systems during a growing season, and the contact with the soil matrix depends mainly on soil bulk density. The objectives of this work were to understand i) the impact of soil tillage, ii) the impact of a mechanically induced compacted soil on sunflower production (quality and quantity). A set of hypothesis were therefore tested: i) minimum tillage and/or soil compaction lead to an alteration of the sunflower growth and development, this alteration leads to ii) a reduction of plant production quantity and iii) oil quality.

- Two field experiments were implemented in two types of soil, a well-drained Glossaqualf soil with strong resilience properties and short water storage; and a Mollic Udifluvent soil with good water status. On the Glossaqualf the factor "soil tillage" was studied, characterized by minimum tillage (MT) and triple tillage (TT). On the Mollic Udifluvent the factor "mechanically induced compaction" was studied, characterized by compacted soil (CS), non-compacted soil (NCS). Soil compaction was characterized each 10 cm on soil trenches, up to 80 cm depth during the crop season. Growth, nutrition indicators and production quality variables were assessed on the different factors during the crop cycle.

- Under soil mechanical constraint, a decrease of root depth (-13% under CS, $P<0.1$), root length (-55% under CS, $P<0.001$), root surface (-67% under CS, $P<0.001$), root volume (-71% under CS, $P<0.001$) and average root diameter (-42% under CS, $P<0.01$) were reported. The root system exploration reduction attributed to soil mechanical constraint had negative impacts on leaf area (-5% under MT at stage M3, $P<0.05$), organs biomass at harvest (-23% of leaf biomass under MT, $P<0.05$), and yield component (-15% of weight of thousand grains under MT, $P<0.05$). Seed protein content (+6% of grain protein under MT, $P<0.05$) and fatty acid balance variation (-12% of oleic acid under CS, $P<0.001$) were also reported. The morphological and physiological changes observed were direct and indirect consequences of soil compaction and minimum tillage. The addition of phenomenon previously described could have act simultaneously or not during the cycle.

- Soil tillage and soil compaction consequences on plant production have been largely studied in many crops. Only few studies have been carried out on sunflower, still less including oil content.

- From literature review and those experiments results, a conceptual model of the involved mechanisms was proposed.

Key words: Sunflower, compaction, yield, oil quality, root system, above ground system.

INTRODUCTION

The sunflower (*Helianthus annuus L.)* is the second French oilseed crop in oil production (tons of oil). In the French sunflower cropping area, the shortening of crop rotation as the sunflower-wheat sequence tends to increase (Lecomte and Nolot, 2011). Reduced tillage practices represents 20% of total practices and only in the French south west (first production area) it reaches 25%, all techniques mixed. Agricultural traffic and/or conservation practices are the cause of variation of soil compaction. Depending of the type of soil, temporary subsoil compaction due to conservation practices can occurred mainly in the first year of practices. Superficial or sub-superficial soil compaction due to agricultural traffic has also been reported largely in many areas (Taboada and Alvarez, 2008). Soil compaction is characterized by a loss of porosity, consequently a loss of water and nutrient availability, an increase of soil bulk density, and of soil penetration resistance facing root growth (Lipiec and Hatano, 2003).

Soil compaction impact on crop growth is a complex process. Soil mechanical constraints negatively impact the root system's growth, which leads to a decrease of below ground and above ground resource acquisition (which leads to an alteration of the root system) and of the use efficiency of those resources; this leads to a reduction of the above ground part of plant growth (which also leads to an alteration of the root system), and finally to a global loss of yield (Lipiec and Hatano, 2003; Sadras *et al*., 2005).

Plant production consequences of soil tillage and soil compaction have been largely studied in many crops (Taboada and Alvarez, 2008). Only few studies have been carried out on sunflower (Bayhan *et al*., 2002), still less including oil content (Petcu and Petcu, 2006), and one include fatty acid content (Sessiz *et al.*, 2008). A multi-location trial was implemented in 2009 and 2010. This study had two objectives: first to understand the impact of soil tillage, then the impact of a mechanically induced compacted soil on sunflower production quality and quantity; by testing on both design a set of three following hypothesis: i) conservation practices and/or soil compaction lead to an alteration of the sunflower growth and development; this alteration leads to ii) a reduction of plant production quantity and iii) oil quality.

MATERIAL AND METHODS

Two experiments were implemented. On the first experiment (field A, 2009), two adjacent soil tillage treatments were compared, with four replicates in each. The soil tillage was characterized by i) minimum tillage (zero tillage, cover crop in spring, MT) and ii) triple tillage (cover crop followed by three perpendicular passes of subsoiler at 60 cm depth in spring, TT). The trial was set up on the experimental farm of the E.I. Purpan (Lamasquère, Midi Pyrenees, France, 43° 30' 11.75'' N; 1° 14' 54.53'' E) in a well-drained Glossaqualf soil. This soil has strong drying properties with low water active storage (1.4 mm per cm of soil). On 2010 experiment (Field B, Auzeville-Tolosane, Midi Pyrenees, France, 43° 32' 35.1'' N; 01° 30' 02.7''E), two adjacent soil treatments were compared. The compacted soil modality (CS) was obtained by several wheel passes of a 3.5 tons tractor on the whole soil surface (soil moisture at 20% between 0 and 20 cm depth, 19% up to 80 cm depth, Lecompte et al., 2003). The non-compacted soil was the result of an autumn traditional tillage under good conditions (NCS).The last trial was set up in INRA experimental farm in a Mollic Udifluvents soil. The soil has low stress properties under the absence of irrigation. Soil bulk density (BD), was estimated by collecting soil samples every 10 cm depth on soil trench, in each replicates, at stage E4 and M3 in 2009, and at stage E2, M0 and M4 in 2010. NK-MELODY (half late, Syngenta Seeds SAS), was the cultivar used in both experiments. In 2009 the soil tillage occurred on the May 5. In 2009, the sowing occurred on the May 6 (6.5 plants.m^{-2}) and the harvest on September 10. In 2010, the soil compaction was carried out on April 14, the sowing on April 27 (6.5 plants.m^{-2}) and the harvest on September 20. No irrigation was applied during crop cycle in any fields. Phenology was monitored each week. The evolution of leaf surfaces was estimated from stage E4 to M4. In each field, three consecutive plants (shoot and root) per replication were sampled at stage E4 and at harvest. Plants above and below ground organs obtained (root, stem, leaf, head, grain) were cleaned, separated and characterized. The organs dry matter was obtained by oven-dried at 70°C shoot organs and root system, and at 45°C for kernels, during 72 hours. Measures on all vegetative systems and yield components were obtained directly. The seed oil quality was obtained from milled sunflower grain samples (20g, three sub-samples per replicates), by near infrared spectroscopy (FOSS NIR System 6200, Ayerdi Gotor et al., 2007). For each sample the reflectance value was measured from 400 nm to 6200nm at an interval of 2nm. As designs used were implemented on adjacent plots, both site received similar management before and during the experiments, except on soil treatment (tillage and compaction). Therefore the authors assumed that the differences observed traduced the consequences of soil treatment only (Taboada et al., 1998). Data were analyzed using analyze of variance (ANOVA, Rgui 2.12.0), a Student test was realized when significant difference appeared at $P<0.05$.

RESULTS

No stresses linked with growth conditions were observed. In 2009 under MT, no difference of BD was observed between the two treatments (mean of 1.4 $g.cm^{-3}$ for both treatment, all horizons confound, data not shown). In 2010, BD was higher in depth at stage E2 under NCS ($P<0.05$), but at stage M0 BD was higher under CS in the top soil ($P<0.05$, mean of 1.4 $g.cm^{-3}$ for NCS and 1.5 $g.cm^{-3}$ for CS, all horizons confounded). Root systems were deeper in 2010 than in 2009 (+40%). In 2009, no differences were observed on root systems. In 2010 under CS, a decrease of root length (-55%, $P<0.001$, table 1), root surface (-67%, $P<0.001$), root volume (-71%, $P<0.001$) and root average diameter (-42%, $P<0.001$), were reported. During all the crop cycle of 2009, the minimum tillage presented a lower leaf surface area compared with the triple tillage treatment. At stage M0, LAI decrease represented 8.5% ($P<0.5$, data not shown). In field B (2010) no significant differences were reported. The shoot biomass were lower in field A (mean of 714 g) than in field B (mean of 1297 g, $P<0.001$).

Table 1. Effect of tillage on root systems architecture at harvest. Field A (MT, TT) and B (CS, NCS). Means of roots systems 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

	MT	**TT**	**CS**	**NCS**
Root Surface (cm^{-3})	133,1 ± 30.5$_{c}$	137,1 ± 29.3	527,8 ± 557.5 ^{b***}	1624,5 ± 358.4 ^{a***}
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***}	1374,8 ± 302.3 ^{a***}
Root Volume (cm^{-3})	8,2 ± 2.6	8,4 ± 3.2	44,6 ± 65.8 ^{b***}	155,1 ± 43.2 ^{a***}
Maximum Root depth	47.5 ± 3.5	45.0 ± 7.1	53.0 ± 0.0 $^{b'}$	61.0 ± 2.8 $^{a'}$
Leaf biomass ($g.m^{-2}$)	74.6 ± 40.6 ^{b*}	96.9 ± 45.9 ^{a*}	152.9 ± 114.0	164.7 ± 161.3
Kernels biomass ($g.m^{-2}$)	172.1 ± 91.1	204.7 ± 114.3	336.4 ± 109.8	358.5 ± 126.9
Shoot biomass ($g.m^{-2}$)	656.9 ± 304.1	773.0 ± 350.9	1242.0 ± 407.6	1352.4 ± 480.9

The grain biomass presented a decrease under MT and CS (-16% and -6% respectively). Seed dry matter and oil content presented an increase in 2010 comparing to 2009 (means of 95.8 % against 95.6 % respectively, and 49.6 % against 44.9 % respectively, $P<0.001$). In 2010, no differences were observed on dry matter or on oil content between the both treatments. Under MT a slight increase was observed in oil content in field A (+3%, 2009). The grain protein content presented a decrease under MT in 2009 (-6%, $P<0.5$, field A). In 2010, the effect of soil compaction on grain protein content was not significant. The oil protein ratio presented contrasting behavior between the years (+3% in 2009 under MT, -2% in 2010 under CS). In seeds, no significant differences were observed for palmitic acid and stearic acid content in 2009 as well as in 2010. The oleic acid content was higher in field B than in field A (22.8% against 15.5%, $P<0.001$, figure 1), consecutively the level of linoleic acid was higher in field A than in field B (76.5% against 69%, $P<0.001$). Field B presented a decrease of 12% of oleic acid in seeds under CS ($P<0.5$). Thus, the level of linoleic acid presented an increase of 5% under CS in the same field ($P<0.5$). Comparable behavior was observed in 2009, with a decrease of 8% of oleic acid content and an increase of 2% of linoleic acid under MT.

DISCUSSION

A conceptual framework has been built from literature and the experiments results (figure 2). Decrease of water and nutrient uptake commonly characterized the plant response to soil compaction (Lipiec *et al.*, 2003). In our experiments, a reduction of root exploration led to a decrease of plant growth (21, figure 2). Those decreases negatively impacted plant physiological status, thus biomass production and allocation status. The morphological modifications were consistent with the known plant response to soil compaction on other species, and related to soil resources scarcity under soil mechanical constraint. Sunflower root plasticity variation under vertical soil constraint remains unknown. However, such plasticity has been observed for wheat in root water absorption under soil compaction (Bengough *et al.*, 2006). From emergence to flowering, leaves function are to synthesize and redistribute reserve to the above ground and below ground (mainly) sink of the plant (arrows (31) and (28), figure 2). From flowering stage, the main functions of leaves are to synthesize and redistribute reserves to above ground part of plant in order to allow grain filling and oil synthesis ((28), Connor and Sadras, 1992). During grain filling leaf duration can also be altered by loss of nitrogen in senescing leaves ((23), Connor and Sadras, 1992). If the plants have difficulties in resources absorption efficiency such as caused by soil compaction (Sadras *et al.*, 2005), this would accentuate the defoliation (23), and so a decrease of above ground resources acquisition (Merrien *et al.*, 1981).

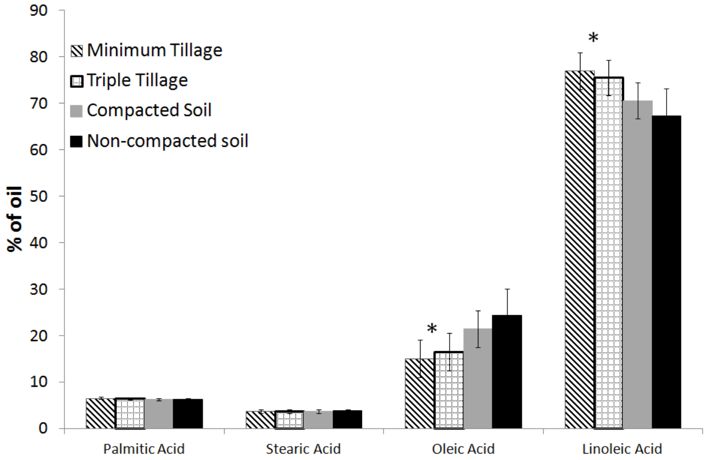

Fig 1. Effect of tillage and soil induced compaction on leaf area oil quality. Means of fatty acid; 2009-2010. Effective: 72. Difference Probability at 0.1,* Significant Probability at 0.05, ** Significant Probability at 0.01, *** Significant Probability at 0.001. Error bar: standard deviation.

Leaf area and leaf elongation decreases characterized usually plant response to soil mechanical constraint (Petcu and Petcu, 2006). In our experiments a significant decrease was observed under minimum tillage in field A at the end of the cycle, a slight increase has also been reported under CS in 2010. This can be explain by each soil water content (higher in field B than in field A), and climatic conditions. Soil compaction increases water matric potential and decreases total available water for plant (8, 18, 19). Thus in case of soil compaction, and soil water scarcity, the plant would have more difficulties to capture water resources (19). At the opposite if soil compaction is not strong enough to unable suitable shoot growth rate (as observed in field B), the increase of soil compaction would have for consequences to favor the root contact with the soil matrix and consequently water absorption, so a slight increase of leaf area. Under soil compaction a loss of biomass is commonly observed in many areas for many crops (Bingham *et al.*, 2010), associated a decrease biomass with a lower nitrogen input (leading also to a reduction of leaf area). In our experiments, only the leaf biomass presented a significant decrease under MT at harvest. However, a slight decrease was observed for all organs and total biomass on both trials. This is consistent with the decrease of leaf area observed in field A. Leaf area is established at the floral initiation, and then result from cells elongation, which decrease under soil compaction (Beemster *et* al., 1996), traducing an alteration of resource efficiency uses induced by soil compaction. In field B, a slight decrease of biomass and a slight increase of LAI could have occurred due to a suitable soil water status allowing good growth conditions under soil compaction (Lipiec *et al.*, 2003). As observed, grain yield decrease under soil compaction has been reported on sunflower (26, 28, 31; Bayhan *et al.*, 2002). During grain filling the sunflower will tend to privileging protein synthesis (which is carried out first after anthesis) under stress conditions, rather than oil synthesis because of its energetic cost (Merrien and 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. The same phenomenon was observed in field B. However the absence of significant result in this field could have been explained by a dilution in the total seed weight which was greater in field B than A. Sunflower oil decreases under soil compaction have been reported (Petcu and Petcu, 2006). No significant results have been reported in any field, however a slight decrease was observed under TT (confirming the resilience of field A soil) and CS. LAI is linked to lipidogenese which is realized in the grain from carbohydrate mainly presents in leaves. As a decrease of LAI has been observed under TT in 2009; a link between those two facts can be made by the lack of resources required for grain filling and lipid genesis (Berger *et al.*, 2010). Thus, the decrease of oil content could have been the indirect result of soil tillage. Under favorable conditions, the cultivar plasticity could have compensate, the loss of LAI in NCS. A significant decrease of oleic acid consequently a significant increase of linoleic acid, have been observed in field B in 2010 (Sessiz *et al.*, 2008). Among environmental factors, temperature is the main source of fatty acids variations, with intercepted solar radiation, nitrogen availability and water supply; management practices act also on their synthesis pathways (Aguirrezabal *et al.*, 2009). Variations of fatty acids content under soil tillage have also been reported (Mirleau-Thebaud *et al.*, 2011). Fatty acid variation linked to water management systems have also been reported (Roche *et al.*, 2006). The Δ12 desaturase activity is directly related to water deficit. Soil compaction affects soil water availability, so could have indirectly acted on Δ12 desaturase activity.

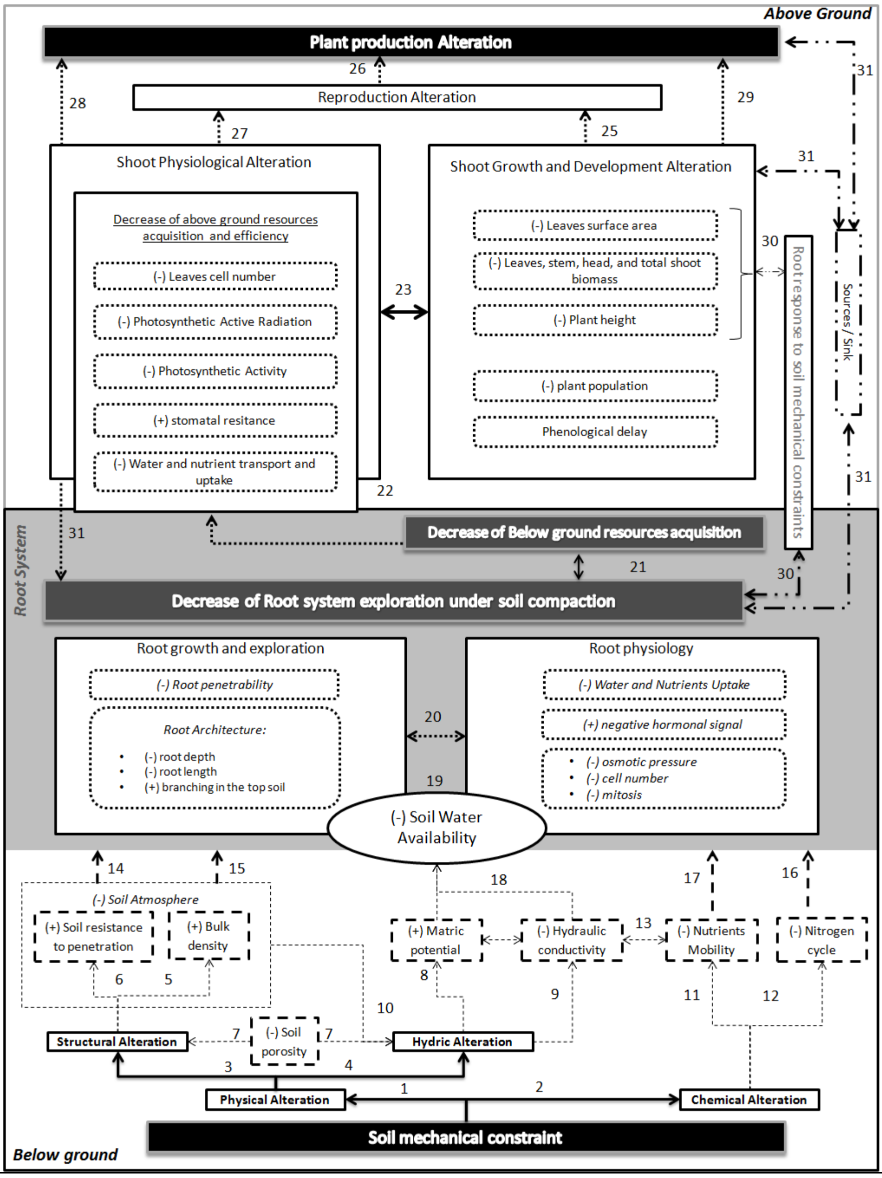

Fig 2. Conceptual of the mechanism of soil compaction actions on sunflower plant. Inspired by Sadras *et al.* (2005) and Lipiec *et al.* (2003). The grey box represents the root system. The white box with black border represents the above ground system. The white box with grey border represents the above ground system. Light grey box represents the decreases of resources uptake and use efficiency. Numbers in bracket represent the actions of soil mechanical constraint on system growth limitations leading to decrease of plant production.

CONCLUSION

Strong modification of sunflower crop under soil compaction was observed in our experiments. The morphological and physiological changes observed were direct and indirect consequences of soil compaction. Under soil induced compaction a decrease of root depth, root surface and root average diameter was reported while an increase of root number of forks occurred. The reduction of resource acquisition and use efficiency (nitrogen and water) attributed to soil compaction, acted on leaf area implementation and duration, yield and yield component variations, seed oil reduction, fatty acid variation. The addition of phenomenon previously described could have act simultaneously or not during the cycle. Since no specific analyses have been realized, and the consequence observed is really closed, it is impossible for the authors to differentiate one pathway from the other.

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