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RESEARCH ARTICLE

Traffic effects on soil compaction and sugar beet (*Beta vulgaris* L.) taproot quality parameters

Francesco Marinello[1], Andrea Pezzuolo[1*], Donato Cillis[1], Alessandro Chiumenti[2] and Luigi Sartori[1]

[1]*University of Padova, Dept. Land Environment Agriculture and Forestry. Viale dell'Università 16, 35020 Legnaro (PD), Italy.* [2]*University of Udine, Dept. Agricultural and Environmental Sciences. Via delle Scienze 206, 33100 Udine (UD), Italy.*

Abstract

Soil compaction is a critical issue in agriculture having a significant influence on crop growth. Sugar beet (*Beta vulgaris* L.) is accounted as a crop susceptible to compaction. Reduction of leaf area, final yield, and root quality parameters are reported in compacted soils. The most obvious visual indicator of topsoil compaction is root depth affected by agricultural tractor and machinery traffic up on the soil. Such indicators are mainly correlated to initial soil condition, tyre features, and number of passages. Monitoring and controlling frequency and position of machine traffic across the field, in such a way that passages are completed on specific, well-defined tracks, can assist with minimization of compaction effects on soil. The objective of the present work was to analyze the subsoil compaction during the growing period of sugar beet with different farming approaches including controlled traffic passages and random traffic. To this end, tests were carried out following each agro technical operation using penetrometer readings in order to monitor the state of cone-index after each step. In addition, at the harvesting time, root quality parameters were analyzed with particular attention to length and regularity of the taproot, total length, circumference, mass, and above-ground biomass. Such parameters were usefully implemented in order to evaluate the effects of controlled traffic passages compared to the random traffic in a cultivation of sugar beet. Results highlight how an increase in crop yield, derived from samples monitored, higher than 10% can be expected with implementation of a careful traffic management.

Additional key words: soil; traffic management; compaction; crop parameters.

Abbreviations used: CI (cone index); CT (controlled traffic area); CTF (controlled traffic farming); CT0 (soil portion not affect by machines compaction); CT3 (lanes undergoing three machines passes); CT8 (lanes undergoing eight machines passes); RT (random traffic area); WW (work widths).

Authors' contributions: Conceived and designed the experiments; performed the experiments: FM, AP, and LS. Analysed the data; contributed reagents/materials/analysis tools: FM, AP, DC, and LS. Wrote the paper: FM, AP, DC, AC and LS.

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Correspondence should be addressed to Andrea Pezzuolo: andrea.pezzuolo@unipd.it

Introduction

Currently, agricultural systems are considered (analyzed and studied) from different points of view compared to the past. One is the protection of the environment in terms of carbon emission and soil characteristics (López-Garrido *et al.*, 2009; Pezzuolo *et al.*, 2014, Basso *et al.*, 2016). Soil characteristics are negatively modified by soil compaction, a side effect of modern agriculture experienced on soils in different parts of the world (Pezzuolo *et al.*, 2017). Soil compaction is defined as "the process by which the soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing the bulk density" (Kroulík *et al.*, 2011). Soil compaction leads to negative consequences such as the reduction of soil porosity, decrease of aeration (McHugh *et al.*, 2009), reduction of saturated hydraulic conductivity and an increase in soil resistance to roots exploration (Balbuena *et al.*, 2003; Valdes-Abellan *et al.*, 2015). Some different approaches have been recently proposed in the last year for fast characterisation of soil condition, mainly consisting of sensors mounted on tines or discs allowing on the go data collection

(Chukuw & Bowers, 2005; Hemmat *et al*., 2008; 2009). A more traditional approach is the measurement of soil mechanical resistance is, assessed taking advantage of a penetrometer with a conical tip. Mechanical resistance, expressed as cone index (CI), is calculated dividing the insertion force by the base area of the cone. Such stop and-go method results a not practical approach in large-scale fields, even when automated, since it is high time consuming and provides only single location variability (Hall & Raper, 2005). Additionally, the method is influenced by soil moisture, which has in general to be considered whenever quantitative analyses are carried out (Ayers & Bowen, 1987; Botta *et al*., 2002; Hummel *et al*., 2004). Despite these limitations, the cone index method is relatively simple and intuitive and widely recognised, also by the ASABE (2001). For this reason, such method was implemented for the present study.

Machines traversing fields are the main source responsible for soil compaction (Chen & Yang, 2015), and their most influencing factors are tire dimension, wheel loads, and inflation pressure. Several mechanical, agronomical, and management solutions are available to mitigate soil compaction. Implementation of low ground pressure tires can allow a reduction of soil compaction on topsoil for about one third of the pressure in comparison with conventional practices (50-80 kPa) (Chamen *et al.,* 1990), and in equipping machines with rubber tracks, a reduction in soil compaction on subsoil is observed (Ansorge & Godwin, 2007, 2008). It is possible to use lighter machines and reduce passages in the fields adopting minimum tillage or no-tillage techniques. Subsoiling allows to enhance soil porosity and water drainage. In addition, compaction is reduced adding organic carbon on soil, depending on soil texture (Kumar *et al.,* 2012; Martín-Lammerding *et al.,* 2013).

Generally, soil compaction leads to negative growth conditions for crops due to high mechanical impedance for roots, decrease in soil aeration, and decrease in water storage (Da Silva & Kay, 1996). There are crops more susceptible to soil compaction than others, as suggested by Koch *et al*. (2008). Sugar beet (*Beta vulgaris* L.) is accounted as a susceptible crop to compaction (Märländer *et al.,* 1998). Reduced emergence, initial growth, final yields, and root quality parameters are reported in compacted soils (Chancellor, 1976; Gemtos & Lellis, 1997; Tolon-Becerra *et al.,* 2011). Compaction can reduce leaf area, dry matter accumulation, and plant population in sugar beet. Furthermore, the total length and distribution of roots in the soil profile can be reduced by topsoil compaction up to 50% (Brereton *et al.,* 1986). Adopting the previous described solutions, such as using rubber track machines, do not lead to a mitigation of problems due to soil compaction in sugar beet (Mosimann *et al.,* 2007).

Controlled traffic farming (CTF) is one of the most interesting and often efficient ways to mitigate soil compaction. In CTF, all or most of operations are performed on well -defined traffic lanes. Machines are equipped with satellite guidance systems which permit crossing repeatedly the same lanes; additionally, machine widths are closely matched with standardized track widths >3 m and narrow tires are implemented (Holpp *et al.,* 2011).

Machines never exit defined traffic lanes, therefore, topsoil is only marginally affected by compaction (Hamza & Anderson*,* 2005; Chamen, 2006). CTF has demonstrated an increase in crop yield related to random traffic farming. Advantages can be significant in root and bulb crop systems for instance potatoes, onions and sugar beet (Gasso *et al.,* 2013; McPhee *et al.,* 2015). The present work is focused on sugar beet, with the aim of analyzing the subsoil compaction during the growing period of sugar beet with different farming approaches: controlled traffic passages and random traffic.

Material and methods

Experimental site

The present study was performed in a private farm in north-eastern Italy in a typical Po Valley field (45.280989 N, 12.006930 E). The soil can be defined, according to the USDA, as silty-loam containing 28.45% sand, 49% silt, 22.55% clay, 1.9% organic matter, 22.5% total $CaCO_3$, 1.31 g/kg total nitrogen, C/N ratio=8.4 and pH (H_2O)=8.0. Before starting the experiments, the area had winter wheat (*Triticum aestivum* L.) as preceding crop, harvested in June, with chopping and spreading of straws.

Description of the experiment

The test field was divided into two equal sub-fields, namely RT (random traffic area) and CT (controlled traffic area), as depicted in Fig. 1. The area was seeded with a total of 84 sugar beet rows, identifying 83 inter-row spaces.

In the RT sub-field, agricultural operations were carried out with a homogeneous/random distribution of tractor lanes over the area. Conversely, in the CT sub-field, agricultural operations were performed adopting controlled traffic basics. To this end, standardized machines work widths (WW) were preliminarily assessed and implemented allowing the tractor to run on defined lanes. Specifically, for the present research, a reference width of 2.70 m was considered for the following operations: seedbed preparation, sowing,

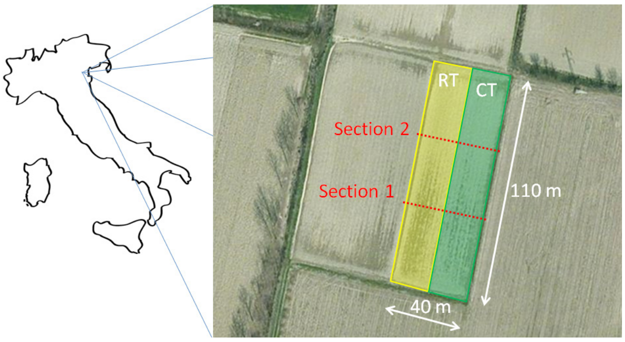

Figure 1. Identification of the experimental field. Measurements were doubled and taken on two different field portions namely *Section 1* and *Section 2*. The two sections crossed rows and inter-rows, characterized by different conditions in terms of number of machines passages for both controlled traffic (CT) and random traffic (RT) areas.

and hoeing operations. Additionally, other agricultural operations characterized by high working widths such as fertilization, weeding, and pesticide applications were carried out using machines with a working width multiple of the reference one. A WW = 13.5 m was then implemented, *i.e.* 5 times greater than the reference width. Reference data, together with working depth are reported in Table 1.

In both RT and CT cases, all of the operations with the exception of harvesting were carried out using a 77 kW 4WD tractor. The weight of the machine excluded implements is 5500 kg, and is supported by 540/65R24 front tyres and 600/65R38 rear tyres, with an inflation pressure of 162 kPa and 182 kPa respectively. A satellite guidance system allowed proper positioning and steering of the tractor, allowing crossing of the same lanes in the field during the entirety of the scheduled agricultural operations. To this end, the authors had at their disposal a Trimble Fm-1000 integrated monitor with RTK GNSS (Real Time Kinematic Global Navigation Satellite System) rover and base station, allowing positioning with an accuracy better than ±4 cm. Other details on implements are given in Table 1. Finally, the field was not interested by irrigation in order to allow observation of the effects of the different traffic managing strategies on crop yield based only on rainfall water. The area was monitored by means of a wireless weather station (Davis Vantage Pro2 Plus) equipped with a rain collector, temperature, humidity and radiation sensors. Main precipitations for the period of interest are reported in Fig. 2.

Data analysis

The experimental field can be considered as homogeneous. However, in order to take rid of or detect some possible variability, and to increase the experimental basis, measurements were doubled and taken on two different field portions (namely *Section 1* and *Section 2* in Fig. 1). The two sections crossed rows and inter-rows, characterized by different conditions in terms of number of machines passages for both CT and RT scenarios:

- CT0, soil portion not affected by machines compaction (*i.e.* no tractor wheels passes during the whole agricultural cycle);
- CT3, lanes undergoing three machines passes;
- CT8, lanes undergoing eight machines passes;
- RT, lanes undergoing a number of passes randomly varying between 0 and 8, and with an average of 1.4 passes.

With regard to the controlled traffic area, 33% of the soil can be classified as CT0, 53% as CT3, and 13% as CT8. For each section, 20 rows and 19 inter-rows were monitored, collecting data related to the four conditions summarized above.

Penetrometer analysis

Penetrometric analyses were carried out after each agricultural operation, in order to investigate the possible evolution in soil compaction correlated to machines passages and its role in final yield. Specifically, seven sets of tests were considered: after seedbed preparation, sowing operation, fertilization, weeding, two pesticide applications and after hoeing before harvesting. For the scope, a penetrometer Eijkelkamp Penetrologger (mod. 06.15.SA) was implemented, allowing georeferentiation of collected data. Measurements has been carried out, with instrument descent speed set in the range 3-4 cm/s and with a maximum depth of 0.80 m, as recommended by ASAE standard (ASAE, 2001). A total of 38 inter-rows was monitored: 19 located adjacently in the CT area and 19 located adjacently in the RT area; each inter-row was sampled in two different positions, lying in correspondence of the two sections. Collected data were

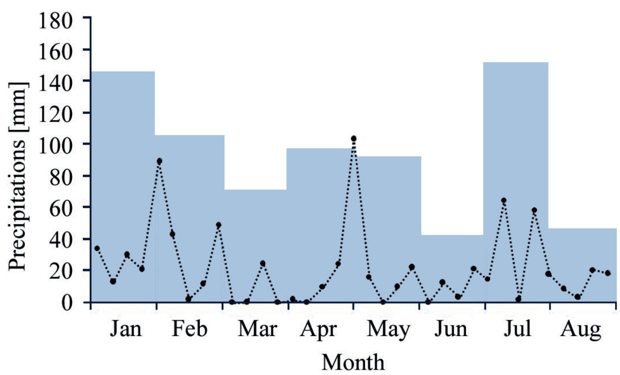

Figure 2. Month total precipitations (histogram bars) and week values (dotted line) in the proximity of the experimental field.

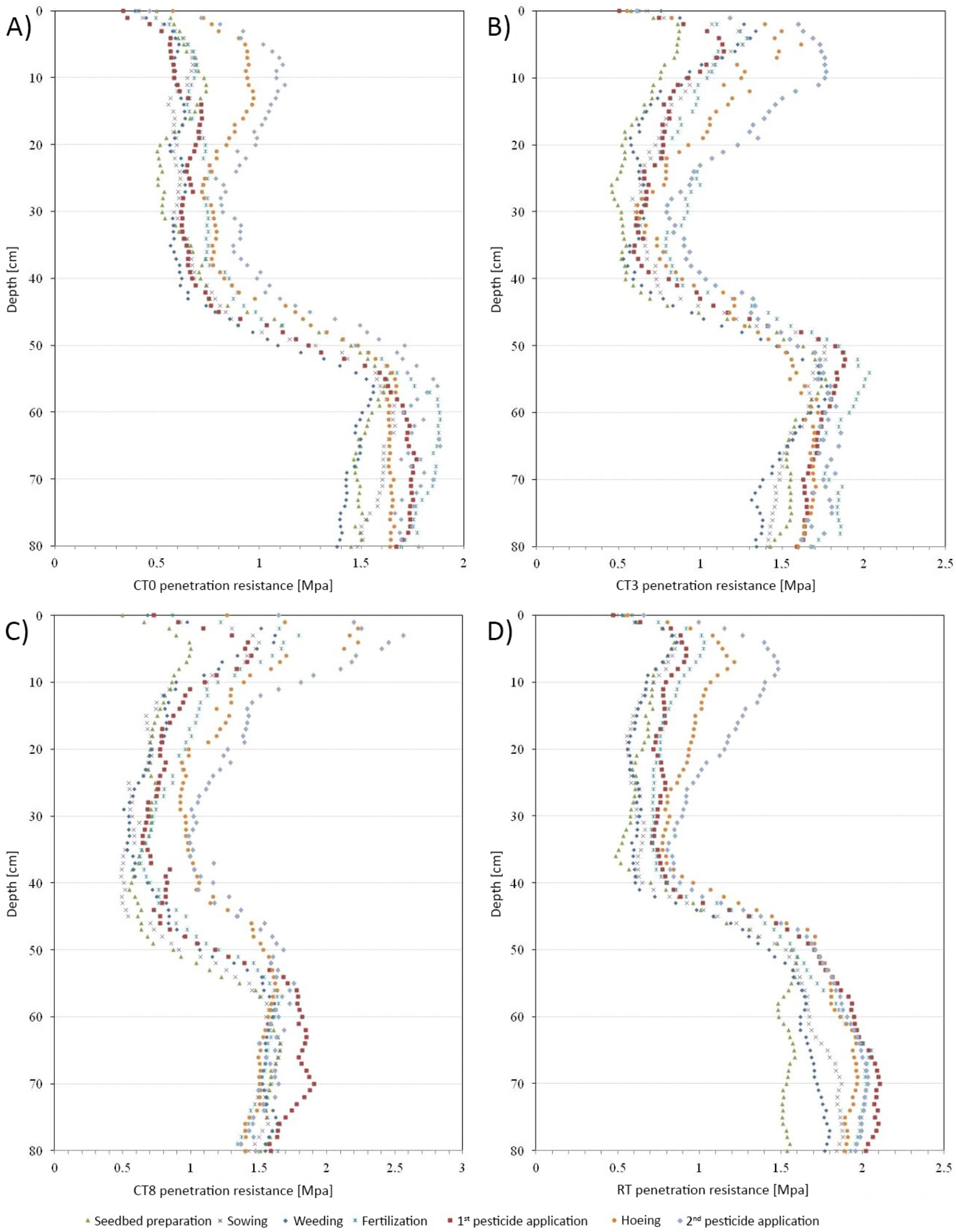

Figure 3. Penetrometer resistance after each operation (seedbed preparation, sowing, weeding, fertilization, hoeing and pesticide applications), in the four scenarios CT0 (A), CT3 (B), CT8 (C) and RT (D).

not corrected for moisture content due to its relatively low variability during the experimental tests. Data were averaged based on relative depth: to this end the zero starting point was defined based on the position of the peak of the second derivative of the measured force. All CT and RT curves were averaged into two mean datasets; additionally, CT curves were averaged based on the number of passages in three corresponding mean dataset.

Sugar beet plants analysis

At the harvesting time, a total representative sample of over 150 sugar beet plants was singularly harvested. Specifically, four plants per row were picked in the test field, in order to have a comprehensive description of the four traffic conditions (CT0, CT3, CT8, RT). In the case of rows sided by different traffic conditions, the plant was ascribed to the most stressed conditions. By way of example: in the case of a plant picked within a row standing between a CT3 and a CT8 line, it was associated to the CT8 group.

Samples were specifically analyzed in terms of some of the most important qualitative parameters for sugar beet: length, total length, circumference, mass, and regularity of the taproot and aboveground biomass as already done by other authors (Gemtos *et al*., 2000; Kenter *et al*., 2006; Kiymaz & Ertek, 2015). Consequently, samples were analyzed to correlate sugar

Table 1. Working width (WW) of the monitored agricultural operations.

Monitored agricultural operations	Date	Working width [m]	Empty weight [kg]	Working depth [cm]	Soil moisture[1] [%]
Seedbed preparation	1st week March	2.7	2430	15	23.0
Sowing operation	1st week March	2.7	1560	4	23.4
Weeding	2nd week March	13.5	800	0	22.5
Fertilization	3rd week April	13.5	800	0	23.9
1st pesticide application	4th week April	13.5	800	0	21.1
Hoeing operation	2nd week May	2.7	560	10	21.7
2nd pesticide application	1 st week June	13.5	800	0	21.5
Harvesting	1st week August	2.7	22000		

[1]Average soil moisture measured 3-5 days after agricultural operation, during penetrometer measurements, on four different positions at 10-25 cm depth

beet parameters to soil compaction due to machines passages between RT and CT.

Results

With regard to penetrometer analyses, Fig. 3 shows average values from different inter-rows after each agricultural operation for the four conditions (CT0, CT3, CT8 and RT).

It can be clearly noted that after the first operation, penetrometer resistances at increasing depths are still very similar, with only negligible differences on the first 5 cm layer. After eight passages (and about after 4 months), the soil has undergone relevant compaction effect, more evident in the case of the CT3 and CT8 condition lanes, but recognizable also in the RT condition. A slight difference can be noticed also in the case of the CT0 condition. This compaction variation is clearly not related to wheels passage but rather to the effect of atmospheric phenomena. The trend can be better appreciated looking at the average penetration resistance at a depth ranging between 5 and 25 cm, where the sugar beet root typically grows (Fig. 4). Specifically, it can be noticed how penetration resistance increases at a rate of about 0.06 MPa after each operation in the case of CT0, 0.10 MPa in the case of random traffic management, and 0.13 MPa in the case of lanes with 3 or 8 passages. In all of the cases, the increase is particular relevant after the first pesticide application. The reason for such behaviour, which is common to all of the scenarios, is ascribable both to the long time passed before the last operation (about two months) but also to the relevant precipitations in the same period.

In order to verify if such soil management difference has a statistically evident effect of sugar beet plant conditions, different parameters were analyzed after harvesting and subjected to ANOVA and Tukey statistical studies. With regard to the regularity of the taproot, no statistical effect was highlighted with an occurrence of forking phenomena which was similar both for the RT and CT conditions.

On the other hand, a significant effect was determined in the case of the taproot circumference. As reported in Fig. 5A, the estimated circumference was higher in the case of un-trafficked lanes (35.4 cm) and lower in the case of trafficked lanes with a minimum in the CT8 condition (27.9 cm). Thus, a compacted soil tends to inhibit the growth of the taproot. Indeed, considering the taproot length (Fig. 5B), average values close to 25 cm were detected only in the case of the CT0 condition, while values lower than 20 cm were in general monitored in trafficked and randomly trafficked lanes. The soil compaction ultimately plays a role in both underground and aboveground plants mass. Results relative to above-ground biomass are reported in Fig. 5C with the same trend described above, and the best performance is always displayed by the un-trafficked

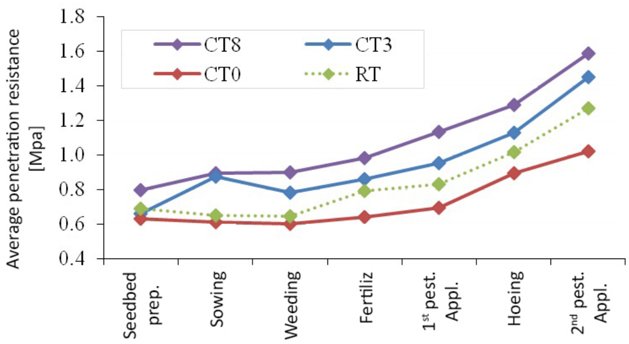

Figure 4. Penetrometer resistance averaged in a depth comprised between 5 and 25 cm, after each operation (seedbed preparation, sowing, weeding, fertilization, hoeing and pesticide applications), in the four scenarios CT0, CT3, CT8 and RT.

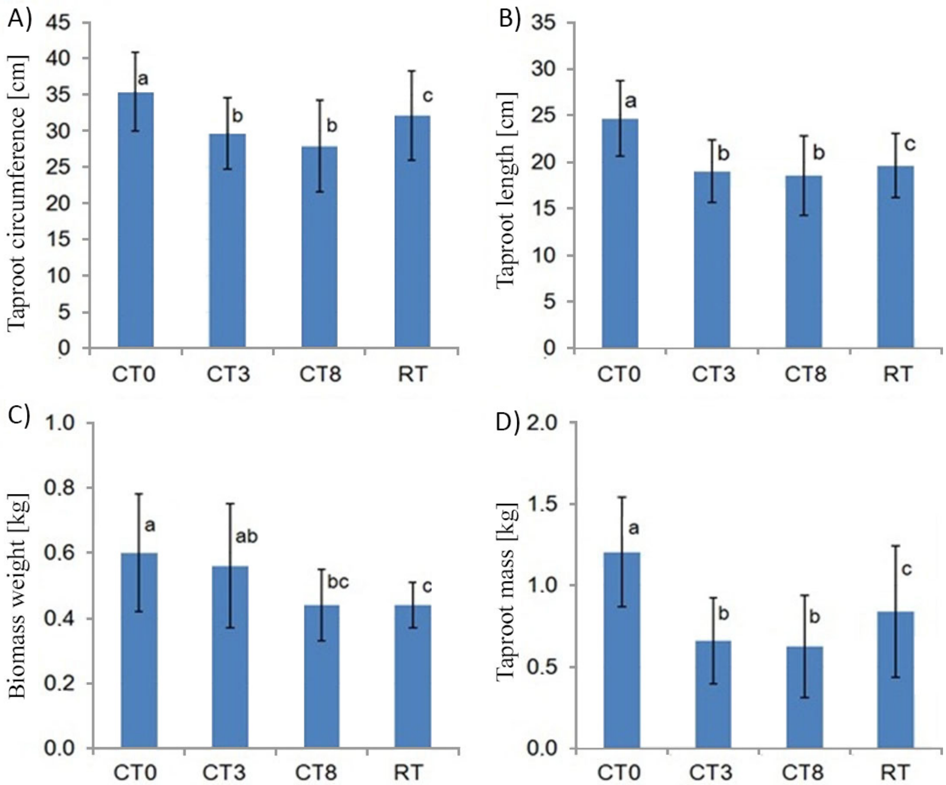

Figure 5. Comparison between taproot circumference (A), taproot length (B), biomass weight (C), and taproot mass (D). Different letters above the histogram bars indicate significant differences between scenarios. Bars indicate standard deviations.

lanes, with a biomass of about 0.6 kg: 27% higher than in the case of random traffic plants or at CT8 condition. Undisturbed soils and healthy above-ground vegetation allow proper growth of the taproot. This is eventually evident on the taproot mass (Fig. 5D) with an average of 1.2 kg, and CT0 sugar beets were 30% heavier than RT ones and 46% heavier than CT3 and CT8.

Discussion

Soil compaction, in both RT and CT conditions, causes a general decline of sugar beet growth. CT fields showed an improvement only in those rows not undergoing traffic stress. As already stated, such rows are only the 33% of the total area, however, they allow a general improvement of the yield in the whole CT area.

Considering the average sugar beet weights in different scenarios and the relative distribution of rows with different passages (33% as CT0, 53% as CT3 and 13% as CT8), a theoretical total yield increase of 1.3% should be detected in the CT area compared to the RT area. On the other hand, 89.5 and 81.1 t/ha actual yields were found respectively for the CT and RT areas. Such values bring the difference at a difference of about 10%, which is far higher than the theoretical one. Such difference was due not only to an increased production but also to a better condition of the plants in a particularly rainy season. Indeed, CT areas are less subject to losses due to water logging, in a percentage which can vary between 5% and 15% depending on the specific season, weather, and rainfall in particular. Such phenomena affecting more seriously RT areas result in a loss of product which amplify the benefits produced by controlled traffic. Such results are in a good agreement with those reported in literature (Chamen *et al*., 1992) relative to European countries, where implementation of CT farming techniques in root and bulb crop systems (such as sugar beet, onions, potatoes, etc.) bring and increased yields of about 4–14%, when compared with RT approaches.

Furthermore, yield difference can be increased by implementing larger machine widths which allow an enhancement of the CT0 incidence on the total area. It is expected that proper application of controlled traffic management can potentially reduce yield losses up to 30%.

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