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Effects of no-till on root architecture and root-soil interactions in a three-year crop rotation

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ABSTRACT

No-till (NT) has repeatedly been reported to result in several environmental advantages, including the reduction of soil erosion, sequestration of carbon from the atmosphere and increase of water retention in soils. However, experimental evidences to date show negative effects of NT on soil physical parameters (*i.e.*, increasing penetration resistance and soil bulk density) and root development of plants, thus reducing crop yield. A three-year field study (2014–2016) was conducted to assess the effects of NT *vs* conventional tillage (CT) on root growth in maize, soybean, and winter wheat, on a silty clay soil in the Northern Italy. Root length density (RLD), diameter class length (DCL), root dry weight (RDW) and roots composition (C and N) in the top 60 cm of soil were measured. The total amount of root C (TRC) was calculated by multiplying RDW by root C content. Relationships among root traits, soil bulk density (BD) and penetration resistance (PR) were investigated using the non-parametric Spearman rank coefficient.

RLD was significantly increased under NT compared to CT in the topsoil (0–5 cm) in maize (6.37 *vs.* 2.03 mg cm^{-3}) and winter wheat (5.38 *vs.* 2.90 cm cm^{-3}), while it was lower in NT than in CT in the deeper soil (5–15 cm) only in maize (3.19 *vs.* 4.53 cm cm^{-3}). RDW was increased under NT compared to CT in the 0–5 cm layer in maize (3.86 *vs.*0.50 mg cm^{-3}), soybean (4.33 *vs.* 0.43 mg cm^{-3}), and winter wheat (0.96 *vs.* 0.38 mg cm^{-3}). NT significantly reduced root C:N ratio of maize (-9%), increased C:N ratio of soybean (+14%), and did not affect C:N ratio of winter wheat. This was mainly related to the effect of NT on coarse roots, which decreased average roots N content. A negative correlation between root traits (RLD, RDW) and soil physical parameters (BD, PR) was found in this study under NT while no correlation occurred for CT. This corroborates the hypothesis that when tillage is abandoned roots are major drivers and detectors of soil physical conditions, which in turn affects roots growth again. Moreover, these results showed that BD did not always represent the main factor affecting root development and the increase of soil strength and particle density under NT did not reduce downwards root growth, which suggests that stability of continuous biopores as induced by NT in well-structured soils is probably much more relevant than the total amount of pores to affect root traits.

1. Introduction

Conservation Agriculture (CA) can be defined as a sustainable management approach of agro-ecosystems to improve and sustain productivity, conserving the environment and increasing at the same time soil fertility (FAO, 2011). CA and, in particular, no-tillage (NT) lead to a series of advantages by saving non-renewable resources and input (Lal, 2008). Reduction of runoff and erosion, mitigation of phosphorus pollution, increase in soil organic carbon (SOC), enhancement of soil water retention (Lal, 2004; Soane et al., 2012) are some of the main outcomes of NT practices. Although NT is recognized as one of the most sustainable soil management systems (Reicosky and Saxton, 2007; Tabaglio et al., 2009a, b) reaching up to 70% of the total cultivated area in South America (Holland, 2004; Derpsch and Friedrich, 2009), it is not widespread in Europe (Basch et al., 2008) where a decrease in crop yield during its establishment has been reported (Brouder and Gomez-Macpherson, 2014; Pittelkow et al., 2015). A series of studies reported that adoption of NT decreased soil quality, increasing soil compaction and bulk density (BD), with negative effects on roots growth and development in a large number of crops (Qin et al., 2006; Guan et al., 2014).

A well-established and deep root system is essential for the absorption of nutrients (Doussan et al., 2006), and water (Gaiser et al., 2012; Mckenzie et al., 2009). Size and distribution of roots are strongly

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influenced by the physical properties of the soil. Bulk density (BD) and aggregate stability (AS) affect the relationship between filled and void spaces (Ball et al., 2005), determining the aeration degree of the soil (Vogel, 2000) and root growth as a consequence. At the same time, it is widely accepted that roots play a major role in macro-aggregate stabilization (Denef et al., 2007) and that their C:N ratio has a great influence on microbial activity (Rasse et al., 2005) and soil priming effect (de Graaff et al., 2013, 2014). In addition, fine roots are very dynamic and play a key role in the ecosystem C cycling (Finér et al., 2007). When NT is implemented oxygen concentration in the subsoil is limited, and, as a result, mineralization of organic matter is reduced and accumulation of organic carbon increases (Kong et al., 2005; Lützow et al., 2006).

Under conventional soil management, tillage practices affect crop growth, nutrient uptake and soil properties (Spedding et al., 2004). However, tillage operations only disturb the structure of the arable topsoil. The structure of subsoil under conventional tillage, as of the whole soil profile under NT soil management, is considerably influenced by roots development and turn-over: during growth, they exceed a pressure which generates a reorganization of the soil pore network (Kolb et al., 2012). After crop harvest and root decomposition, dug channels remain empty in the soil, forming biopores (Jones et al., 2004). Soil burrowing animals, such as anecic earthworms, can influence soil structure. When tillage intensity is reduced, the population of anecic earthworms can be promoted (Curry et al., 2002; Peigné et al., 2009), which in turn can contribute to the formation of biopores (Ehlers, 1975; Joschko et al., 1989). Conversely, a series of studies report that topsoil under NT is usually cooler and moister (Dwyer et al., 1996; Muñoz-Romero et al., 2012), characterized by a higher BD (Munkholm et al., 2012; Soane et al., 2012), that causes high penetration resistance (PR), than under conventional tillage (CT) (Chassot et al., 2001). Under NT these negative features can cause a soil structure stratification, which can limit root penetration and promote a lateral and superficial root development (Qin et al., 2006), especially in fine-textured soils where the lack of aeration is usually alleviated by tillage (Agrawal et al., 1989; Gupta and Woodhead, 1989).

Differences of root spatial distribution, quantified as root length density (RLD) index, between CT and NT have been investigated in a number of studies but with controversial results. Some results showed that RLD at flowering was higher under NT than under CT in sandy and well-drained sites (Hilfiker and Lowery, 1988), while in fine-textured soils roots were generally more abundant, finer and longer under CT, because of a higher root downward progression, than under NT (Li et al., 2017a). However, other studies found higher RLD in NT than in CT also in clay-enriched and silty clay loam soils (Baligar et al., 1998; Holanda et al.,1998), because of a greater and deeper water accumulation (Lampurlanés et al., 2001). Furthermore, other factors should be considered as key drivers affecting root development: soil compaction, for instance caused by wheel traffic, reduced RLD in all conditions (Hilfiker and Lowery, 1988), particularly under CT due to a less stable soil structure than under NT. Tillage could periodically mitigate soil compaction, while in NT this turns into a progressive BD and PR increase, thus resulting in reduced root density and distribution as compared to CT in the long-term (Karunatilake et al., 2000; Sheng et al., 2012). However, when soil compaction under NT was controlled, RLD was not reduced by NT (Hughes et al., 1992; Dal Ferro et al., 2014).

To our knowledge few studies report on the effect of tillage *vs* NT on root dry weight (RDW) and no one on carbon and nitrogen content of roots. The objective of this work was to study how (i) the main traits of root architecture and (ii) its composition (C and N) are affected by soil management (CT *vs* NT) in the top 60 cm of soil under maize, soybean, and winter wheat. The relationships among roots, soil compaction and bulk density were also investigated.

Table 1
Physical and chemical properties of the topsoil (0–30 cm depth) at the beginning of the experiment.

Soil Property	Unit of Measure	Value
Sand (2–0.05 mm)	g kg^{-1}	122
Silt (0.05–0.002 mm)	g kg^{-1}	462
Clay (< 0.002 mm)	g kg^{-1}	417
pH (KCl 1 M) H_2O		5.4
$CaCO_3$ (volumetric)	g kg^{-1}	2
Organic Matter (Walkley and Black)	g kg^{-1}	21
total N (Kjeldahl)	g kg^{-1}	1.2
available P (Na bicarbonate 0.5 M, pH 8.5)	mg kg^{-1}	31.9
exchangeable K (Ba chloride, pH 8.1)	mg kg^{-1}	294
C.E.C. (Ba chloride, pH 8.1)	cmol^{+} kg^{-1}	29.7

2. Materials and methods

2.1. Experiment and treatments

The field experiment was carried out at the CERZOO experimental research station in Piacenza (45°00′18.0″ N, 9°42′12.7″ E; 68 m above sea level), Po valley, northern Italy. Soil was silty clay; *fine, mixed, mesic, Udertic Haplustalf* (Soil Survey Staff, 2014). Main physic-chemical properties of soil are shown in Table 1. The climate is temperate; mean annual temperature and precipitation are 12.2 °C and 890 mm respectively. Climatic data were collected from an automated meteorological station positioned in the experimental field (Table A1 in Supplementary material).

The experimental design was a randomized complete block (RCB) with four repetitions and two treatments: conventional tillage (CT) and no-tillage (NT). The single plot size was 1430 m^2 (65 m × 22 m). The experiment was established in 2010 to compare: (i) CT, which included an autumn plowing (35 cm) and two passages of rotating harrow in spring (15–20 cm) to prepare the seedbed, and (ii) NT, consisting of direct sowing on untilled soil using a double-disk opener planter for seed deposition. NT and CT planters were calibrated in order to obtain for each crop the same sowing depth in both treatment.

Crop sequence was a three-year crop rotation, which included winter wheat (*Triticum aestivum* sub. aestivum L.), maize (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.). All plots had been subjected to conventional tillage before starting the experiment. Crop residues were incorporated into the soil in the CT plots, while they were left on the soil surface in NT plots. During non-growing seasons, a cover crop of hairy vetch (*Vicia villosa* Roth.) was sown in NT plots right after harvesting the previous main crop. Two weeks before sowing of the following main crop, hairy vetch was terminated by spraying 3 L ha^{-1} of Roundup Platinum (Glyphosate 79.5%).

In 2014, plots were cropped with maize, fertilized at a rate of 250 kg N ha^{-1}. Sowing was carried out on April 24th (sowing depth: 3–4 cm), using a maize hybrid FAO maturity group 600 (SNH 9609), and harvest took place on September 24th, after physiological maturity when kernel humidity was 22%. Weeds were controlled at four leaves visible stage by spraying 1.2 L ha^{-1} Ghibli (Nicosulfuron 4.2%) and 1.3 L ha^{-1} Calaris (Terbuthylazine 29.3%; Mesotrione 6.2%). In 2015 the main crop was soybean with a maturity group 1- (Cv. Bahia), which was planted on May 8th (sowing depth: 3–4 cm) and harvested at the beginning of October (1st). No fertilizer was applied during soybean growing season, while weeds were suppressed by using 2 L ha^{-1} Stratos (Cicloxidim 21%) and 5 g ha^{-1} Harmony (tifensulfuron-methyl 75%). Durum winter wheat (Cv. Monastir) was sown (sowing depth: 2–3 cm) after soybean harvest on 19th of November and it harvested on 8th of July. A rate of 170 kg N ha^{-1} was applied at the end of February. Both